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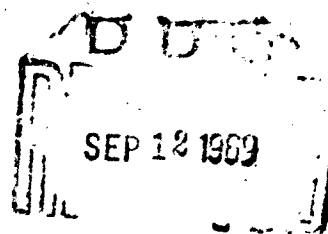
AFAPL-TR-69-68
VOLUME I

GENERATION OF INERTING GASES FOR AIRCRAFT FUEL TANKS BY CATALYTIC COMBUSTION TECHNIQUES

R. B. Wainright
A. Perlmutter
American Cyanamid Company

TECHNICAL REPORT AFAPL-TR-69-68 VOLUME I

AUGUST 1969



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Coding of Catalysts

<u>Catalyst</u>	<u>Designation</u>	<u>Supplier</u>
Code A	AERO-BAN [®]	American Cyanamid Company
Code B	"room-temperature" shift	" " "
Code C	PAA-3	" " "
Code D	G-66B	Chemetron Corporation (Girdler)
Code E	G-3A	" " "
Code F	G-56B	" " "
Code G	902	W. R. Grace Company (Davison)
Code H	906	" " "
Code I	908	" " "
Code J	V-0601T	The Harshaw Chemical Company
Code K	V-0701T	" " "
Code L	HC-2MF	Engelhard Minerals & Chemicals Corp.
Code M	"N" AERO-BAN [®]	American Cyanamid Company

**GENERATION OF INERTING GASES
FOR AIRCRAFT FUEL TANKS
BY CATALYTIC COMBUSTION TECHNIQUES**

Volume I

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A. Perlmutter**

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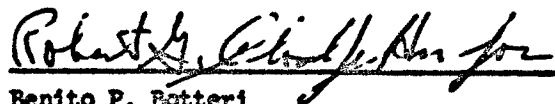
FOREWORD

This report was prepared by the Central Research Division, American Cyanamid Company, and covers work performed under Contract Number F33615-68-C-1500, Project No. 3048 - Fuels, Lubrication, and Hazards, Task 304807, Aerospace Vehicle Hazard Protection. Administration was provided by the Air Force Aero Propulsion Laboratory, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, with Mr. Robert E. Cretcher, APFH Hazards Branch, acting as Project Engineer. The contract was initially funded with Laboratory Director's Discretionary funds.

The effort reported herein was performed in the period April 1968 through June 1969, at Cyanamid's Stamford Research Laboratories in Stamford, Connecticut. Experimental work was performed by Messrs. J. R. Johnson, W. E. Kuehlewind, H. Y. Li, J. P. Mazur, and A. Perlmutter. Conceptual design studies were performed by Mr. A. Perlmutter. Mr. D. R. Goodrich served as Project Leader during the initial part of the program, and Mr. R. B. Wainright as acting Project Leader during the remainder of the program. Cyanamid's technical management throughout was provided in the person of Mr. Wainright.

This document was submitted by the authors in June 1969.

This technical report has been reviewed and is approved.



Benito P. Botteri
Chief, Hazards Branch
Fuels, Lubrication and Hazards Division

ABSTRACT

The feasibility of inerting the ullage spaces in aircraft fuel tanks via a catalytic combustion technique is evaluated. The technique utilizes nitrogen from the surrounding atmosphere as the principal component of the ballast gas admitted to the tanks. Free oxygen is reduced to safe levels by means of catalyzed reaction with a small fraction of the aircraft fuel. Before the combustion gases are admitted to the fuel tanks, the water content is reduced by condensation and by contact with a desiccant. Experiments were conducted to select and evaluate catalysts for the combustion reaction, and desiccants for water removal. Heat and material balances were prepared. Experimental and literature data were used for conceptual designs of inerting equipment that would provide target performance at all times (including powered dives) during missions typical of a tactical aircraft, a military transport, and the SST. Based on these unoptimized, preliminary designs, it was determined that complete inerting protection and control over the water admitted to the fuel tanks can be provided at a penalty of from 1.8% (transport) to 6.4% (tactical) of the initial fuel weight. These figures reflect industrial plant equipment weights, and substantial reductions are expected through use of flightweight equipment of optimized design. Recommendations are made for further study and development.

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LIST OF ABBREVIATIONS AND SYMBOLS

SYMBOL	DEFINITION	UNIT
A	area	in ² , ft ²
A	frequency factor (kinetics)	dimensionless
A _a	annular area	in ² , ft ²
A _f	fin surface area, per linear foot	in ² , ft ²
A _f	wall effect factor	dimensionless
A _o	bare tube area, per linear foot	in ² , ft ²
a _g	flow area, excluding projected area of tubes	in ² , ft ²
a _t	interior cross-sectional area of tube	in ² , ft ²
AU	overall rate of heat transfer	BTU/hr-°F
B	energy of activation ÷ gas constant	
b _d	duct width (radial reactor length)	in, ft
b _f	fin height	inches
BG	ballast gas	
BTU	British Thermal Unit	
C, c	specific heat	BTU/lb-°F
c	orifice discharge coefficient	dimensionless
C _A	outlet conc. of species A (kinetics)	% volume
C _{AO}	entering conc. of species A (kinetics)	% volume
cfm	volumetric flow rate	ft ³ /min
D, d	diameter	in, ft
d _e	equivalent diameter	in, ft
D _p	equivalent particle diameter	inches
E	energy of activation (kinetics)	kcal/g-mole
e	natural logarithm base	

SYMBOL	DEFINITION	UNIT
f	friction factor (fluid dynamics)	dimensionless
ΔP_a	pressure drop	ft of fluid
F_T	temperature difference factor	dimensionless
G	mass velocity	lb/hr-ft ²
g	gravitational constant = 32.2	ft/sec ²
gpm	volumetric flow rate	gal/min
h	height	in, ft
h	enthalpy	BTU/lb
h	film coefficient (heat transfer)	BTU/hr-ft ² -°F
h_d	duct height	in, ft
HE	heat exchanger	
ID	inside dimension, inside diameter	in, ft
J_{hr}	heat transfer factor for transverse fins	dimensionless
k	thermal conductivity	BTU/hr-ft ² -(°F/ft)
K	reaction rate constant (kinetics)	v/v-hr, v/v-sec.
KW	kilowatt, energy unit	
L, l	length	in, ft
ΔT_{MD}	log mean temperature difference	°F
MW	molecular weight	lb/lb-mole
N	number per unit length	#/in, #/ft
N	molar rate	lb-moles/min or hr
OD	outside dimension, outside diameter	in, ft

SYMBOL	DEFINITION	UNIT
P	perimeter	in, ft
P	absolute pressure	lb/in ² abs, psia
P	gage pressure	lb/in ² gage, psig.
P _p	projected perimeter per linear foot	in/ft, ft/ft
ΔP	pressure difference	lb/in ² , psi
Q	heat flux	BTU/min, BTU/hr
Q	volumetric flow rate (kinetics)	ft ³ /min, ft ³ /hr
ΔQ	heat content differential	BTU/min
R	temperature group, t_1-t_2/t_4-t_3	dimensionless
R	universal gas constant	BTU/mole-°F
r, R	radius	in, ft
r _b	inside fin radius	inches
R _{do}	fouling factor	dimensionless
Re	Reynolds number	dimensionless
r _e	outside fin radius	inches
S	temperature group, t_4-t_3/t_1-t_3	dimensionless
S	tensile strength	lb/in ²
S, s	specific gravity	dimensionless
S _p	specific gravity of fuel	dimensionless
S _f	frictional surface	feet ²
S _L	centerline distance between tubes in two banks arranged in triangular pitch	in, ft
SS	stainless steel	
S _T	centerline distance between adjacent tubes in bank	in, ft
SV	space velocity, volumetric flow rate ÷ volume of reaction zone	sec ⁻¹ , hr ⁻¹

SYMBOL	DEFINITION	UNIT
t	temperature	$^{\circ}\text{F}$
T	absolute temperature	$^{\circ}\text{R}$
T_c	caloric temperature, hot fluid	$^{\circ}\text{F}$
t_c	caloric temperature, cold fluid	$^{\circ}\text{F}$
th	thickness	inches
U	overall heat transfer coefficient	$\text{BTU/hr-ft}^2\text{-}^{\circ}\text{F}$
V	volume	in^3, ft^3
v, V	volumetric flow rate	$\text{ft}^3/\text{min}, \text{ft}^3/\text{sec}$
v	velocity	ft/sec
\bar{V}, \bar{v}	specific volume	ft^3/lb
V	cumulative flow of gas (water removal tests)	liters
V_m	molar volume	$\text{ft}^3/\text{lb-mole}$
V_o	velocity of fluid in empty duct	$\text{ft}/\text{sec}, \text{ft}/\text{min}$
V_s	distance between two banks of tubes	in, ft
V_{NF}	net free volume (in a duct)	foot^3
v_t	volume per linear foot	ft^3/ft
w	weight per unit length	$\text{lb}/\text{in}, \text{lb}/\text{ft}$
W	rate of flow, weight	$\text{lb}/\text{min}, \text{lb}/\text{hr}$
λ	heat of vaporization	BTU/lb
μ	viscosity	centipoises, $\frac{\text{lb}/\text{ft-h}}{\text{lb}/\text{ft-s}}$
ρ	density	lb/ft^3
ϕ	viscosity ratio	dimensionless
η	fin efficiency	dimensionless

SECTION I

INTRODUCTION

1. BACKGROUND

Among the hazards that must be faced in the planning, design, and operation of liquid-fueled aircraft is the problem of fire and explosion in the fuel tanks. The isolation of fuels from ignition sources, such as hot engine parts, impact sparking, electrical circuit malfunctions, and lightning or other static discharges, has been the subject of considerable effort so that substantial protection is now available in current operational aircraft⁽¹⁾. Serious problems can still be identified, however, associated with flammable fuel vapor-air mixtures within the fuel tanks. Tactical aircraft operating in combat areas are subject to fuel tank penetration by enemy incendiary and bursting rounds which would ignite the mixture. In the case of advanced supersonic military or commercial aircraft, such as the Supersonic Transport (SST), it is anticipated that aerodynamic heating may generate tank wall temperatures above the autoignition point of the mixed vapors⁽²⁾. Once the vapors become ignited, combustion could proceed with sufficient speed to cause a substantial pressure rise, despite the presence of tank venting equipment, leading ultimately to disastrous structural failure.

The present report gives the results of an R & D study directed toward the evaluation of a proposed aircraft fuel tank inerting subsystem. The basic concept is to use the nitrogen in the atmosphere as ballast gas to displace fuel delivered to the engines. Free oxygen accompanying the atmospheric nitrogen is reduced to a safe level by conversion to carbon dioxide and water by means of a catalytic combustion process which consumes a very small fraction of the aircraft fuel. The water is removed from the ballast gas before it enters the fuel tanks.

2. OBJECTIVE

The objective of this technical effort was to establish the feasibility of the proposed inerting subsystem, and to develop the basis for preliminary subsystem design. The performance goals toward which the investigation was directed are as follows:

- a. Oxygen concentration of 2 to 9% (volume) in the ballast gas.
- b. Maximum water concentration of 5 ppm in the ballast gas.
- c. Minimum catalyst life of 50 flight hours without regeneration.
- d. Regeneration capability by a technique which does not require unusual or highly intricate equipment, enabling the catalyst life to reach a minimum of 500 flight hours.

- e. Inerting subsystem weight not to exceed 0.4% of the original fuel weight.
- f. Capability to supply ballast gas during a dive in which the ambient pressure change reaches 14.7 psi/minute.
- g. Capability to function with JP-4, JP-5 or JP-7 fuel.
- h. Capability to provide the desired inerting protection for both subsonic and supersonic aircraft at altitudes of 0 to 80,000 feet.
- i. Conformance to environmental test requirements as set forth in MIL-Std-810.

3. TASK DESCRIPTION

At the outset of work, the investigation was divided into three principal parts, and two of these were subdivided into individual tasks, all of which are described below.

a. Catalytic Combustion (Task I)

(1) Literature Survey

Determination of catalytic systems and techniques reported in the literature, used either commercially or in research.

(2) Screening of Commercial Catalysts

Identification of commercial catalysts having possible utility for the proposed subsystem, and comparative evaluation of their activities.

(3) Screening of New Catalysts

Evaluation of catalysts that are not available commercially but have shown high activity in laboratory tests or might be expected to do so from fundamental considerations.

(4) Basic Process Studies

Applies to catalysts selected under (2) and (3). Includes analysis of the effects of temperature, pressure, space velocity, and other conditions.

(5) Effect of Fuel Composition

Evaluation of the effects of changes in fuel type on catalyst performance, with emphasis on use of jet fuels in place of simple hydrocarbons, and effects such as rate of coking and rate of activity loss.

(6) Optimization and Regeneration Studies

Determination of optimal operating conditions for the catalytic reaction, taking into account interrelationships between temperature, pressure, flow rate, catalyst particle size, pressure drop in catalyst bed, and the like. The primary goal will be maximum conversion consistent with catalyst stability. Regeneration techniques are to be studied from the standpoints of conditions to be used, the period of active service between regenerations, and the number of regenerations that can be performed before the catalyst must be replaced.

b. Water Removal (Task II)

(1) Literature Survey

Collection and study of published information on drying techniques, with emphasis on achievement of high rates and efficiencies (i.e. low exit water concentrations) under the expected operating conditions.

(2) Selection of Feasible Methods

Comparative evaluation of drying techniques and agents, individually and in combination, based on information in the literature and consideration of the performance goals.

(3) Process Studies

Analysis of the effects of temperature, pressure and flow rate on both capacity and efficiency of the selected drying agents.

(4) Effect of Fuel Composition

Evaluation of possible adverse effects of jet fuels and components thereof on the most effective water removal agent or agents.

c. Conceptual Design (Task III)

Design of subsystem based on literature data and data generated in the experimental program. Major considerations are to be minimum weight, maximum reliability, and compatibility with the main system (aircraft) of which it is a part.

SECTION II

SUMMARY

A study of the proposed scheme whereby inerting protection for aircraft fuel tanks is provided by gas produced in the catalytic combustion of a small fraction of the aircraft fuel was conducted. There were three main tasks: catalytic combustion studies, a study of methods of removing combustion water, and conceptual design. It was shown that the inerting subsystem is technically feasible.

Conceptual designs were directed toward inerting subsystems for a tactical military aircraft, the C-141 transport, and the SST. It was specified that protection against ignition of vapors in fuel tanks be provided at altitudes up to 80,000 feet and at rates of descent equivalent to an ambient pressure change of 14.7 psi/min. Ballast gas entering the fuel tanks is to contain 2 to 9% free oxygen, and no more than 5 ppm water, except for the C-141 aircraft, where it was specified that the ballast gas contain no more than 0.001 lb water/lb dry gas, or 1,555 ppm V/V.

The flow of ballast gas varies widely. In the SST, it is 15 cfm at level cruise, 360 cfm during normal descent, and 3650 cfm during a powered emergency dive (all values at the respective prevailing ambient pressure). From 13 to 16 pounds of combustion water is produced and removed during a 3-hour flight having one ascent and one descent. Only 0.006% of the initial fuel supply is needed to generate the inert ballast gas.

In general, the same approach was used in developing the conceptual design for each of the three types of aircraft. A few variations were made intentionally in order to point out and compare alternate means of attacking a problem. The designs used were not optimized, and weights were estimated using methods normally applied to chemical processing equipment. Two designs of inerting equipment for the SST were prepared, representing a "normal" flight and a flight aborted by an emergency, powered descent. In the former case the weight of all equipment, most transfer lines, and catalytic and drying agents (exclusive of insulation, controls, and any required supporting structure) was found to be 4,640 pounds. This represents 2.3% of the original fuel weight, as compared to the target value of 0.4%. The weight breakdown is as follows:

Combustor and feed equipment	831 lb
Heat exchangers (gas coolers)	2110
Gas drier	1393
Cooling water supply	306
Total	4640 lb

In the latter case, the weight of all the equipment is 8,229 lb or 4.1% of the original fuel weight. The weight breakdown is as follows:

Combustor and feed equipment	967 lb
Heat exchangers	2212
Gas drier	4715
Cooling water supply	335
Total	8229 lb

A similar analysis prepared for the tactical aircraft yielded the following weight breakdown (exclusive of insulation, controls and any required supporting structures):

Combustor and feed equipment	165 lb
Heat exchangers	524
Gas drier	305
Water supply	70
Total	<u>1064</u> lb

which represents 6.4% of the initial fuel weight.

An inerting subsystem was designed in concept for the C-141 aircraft, and the weights were as follows:

Combustor and feed equipment	378 lb
Heat exchangers	1273
Gas drier	836
Water supply	176
Total	<u>2663</u> lb

which represents 1.8% of the initial fuel weight.

Possibilities for reducing the weights toward the target level include optimization of the design, i.e. use of advanced materials, modification of equipment types and dimensions to obtain more compact, light-weight units, and reduction in the temperature at which coolants are available. Also, alternate heating and cooling techniques may, upon investigation, effect a net reduction in weight. Information received after completion of the work reported herein indicates that design optimization which incorporates flight hardware techniques can result in an order-of-magnitude reduction in the weights of some components.

In the normal SST flight, the combustor design is based on 96% conversion of oxygen (leaving 1% in the dry ballast gas) at the maximum demand rate of 360 cfm. This provides considerable margin for catalyst deactivation, in the interest of a long service life. In all the other situations, combustor design is based on 75% conversion (5.5% residual oxygen) at the maximum demand rate. This provides a smaller margin against deactivation.

The main criterion in reactor sizing is the rate of demand for ballast gas. There is no weight change during operation, only a gradual diminishing of catalyst activity. In contrast, the drier must be designed to perform at design efficiency while holding an accumulation of water. Both catalyst and drying agent must be regenerated. The frequency of catalyst regeneration to restore performance loss due to the presence of carbonaceous deposits is not established. In fact, the catalyst performs well with deposition of 10.6% carbon. The quantity of drying agent required to provide 10 ppm residual water concentration at the peak demand rate in the tactical aircraft provides capacity for 73 hours of operation between regenerations. In the C-141 aircraft, the quantity of agent needed to satisfy the exit water concentration limit provides capacity for 230 hours of operation. In the SST normal flight situation, the weight of the drying agents must be increased by 187 pounds or 23% in order to increase the service time from 28 to 50 hours, which is the performance target.

Regeneration of either catalyst or drying agent can be accomplished in place with the assistance of a ground service truck, or by removal of the agents (in prepackaged cartridges) and substitution of regenerated charges previously processed at a ground facility. Based on a test using an excess of JP-4 fuel of MIL-T-5161G quality, it is known that the catalyst can be used at least 60 hours without regeneration.

The ultimate service life of both the catalyst and drying agent remain to be demonstrated. However, it is estimated that the catalyst life will equal or exceed the 500-hour target value. The time for replacement of the drying agent will be indicated by abnormal flow behavior (rise in resistance to flow) and/or by substandard drying performance. Replacement requires removal of the combustor (or cartridge) and drier (or cartridge) from the aircraft, and processing at a ground station.

The combustion air in this subsystem is drawn from the high pressure stage of the engine compressors. Fuel en route to the engines is used as a coolant, but must be supplemented by water, which is evaporated in the combustor coils and dumped as steam. In the tactical aircraft analysis, it was found that 31% of the combustion heat is transferred to the fuel, and 69% to a special cooling water supply.

Of the various catalysts evaluated, one designated Code A was selected for in-depth studies because of its

- high level of activity for conversion of oxygen
- relatively low operating temperature
- best performance under experimental conditions
- satisfactory physical and mechanical properties

Removal of the reaction heat by evaporation of water in the combustor coils necessitates a supply of cooling water for the subsystem. An additional benefit from this water is realized by directing the cooling water to the coils in the gas drier before it enters the combustor. This provides the lowest practical drier bed temperatures, and therefore the greatest removal of water. CaCl_2 is the best high-capacity agent and zeolite the best high-efficiency agent, of those studied. Combinations of the two are used in most of the case analyses.

The data for each of the aircraft were analyzed to determine the effect of ballast gas moisture content on subsystem weight. In each case, the greatest weight (and lowest moisture content) corresponded to the target moisture level, and the lowest weight to the removal of water by condensation only, i.e. no drying agent employed. An intermediate value was calculated for each aircraft representing use of condensation plus a single drying agent, CaCl_2 . The results are presented in Table I-J and Figure 1-J, Appendix J, where it is seen that the maximum possible reduction in weight ranges from 35% to 61% according to the type of aircraft and choice of flight plan.

SECTION III

CATALYTIC COMBUSTION STUDIES

1. GENERAL

Catalytic combustion to remove free oxygen from air is the key step in this proposed method of obtaining inert ballast gas, and offers distinct advantages over uncatalyzed combustion. First, the reaction temperature is far lower in the catalytic system. At present, a difference in excess of 2500°F. can be claimed, but this difference is subject to enlargement as investigations directed toward more active catalysts continue. Ability to operate at lower temperatures is advantageous in that less exchange of heat is involved in preheating the reactants and cooling the products, therefore fewer penalties in complexity, pressure drop and subsystem weight. A substantial lowering of preheat temperatures can reduce or eliminate pyrolytic decomposition of the fuel, and thus prevent or curtail fouling of the heat exchange surfaces and other possible deleterious effects. Since the combustion reaction is exothermic, thermodynamic considerations indicate a higher attainable equilibrium conversion of oxygen as the temperature of reaction decreases. A further advantage offered by catalytic combustion is the prospect of obtaining more complete reactions under fluctuating operating conditions such as might exist on an aircraft. This is expected because the catalyst bed provides an abundant quantity of hot and active surfaces throughout the internal volume of the reactor which can be expected to counter the effects of abnormalities in composition and temperature. Finally, the catalyst can impart a selectivity leading to a more favorable distribution of gaseous end-products, e.g. a high ratio of carbon dioxide to carbon monoxide, hence a greater uptake of free oxygen.

Implicit in the above discussion is the idea of designing and formulating a catalyst which is well suited to this specific job. Normally, this is a major undertaking, particularly when the task at hand differs substantially from other tasks for which catalysts have already been developed. In the present case, the strategy was to emphasize the test and evaluation of existing commercial catalysts that might be recommended by virtue of previous characterization work. In this way a time-consuming catalyst development program might be avoided, or at least deferred until a later phase.

2. RESULTS AND DISCUSSION

a. Literature Survey

The literature survey covered the design and experimental analysis of heterogeneous catalytic reaction systems, theories of the effect of temperature, flow rate, and pressure on heterogeneous reactions, and the formulation of efficient hydrocarbon oxidation catalysts. Consultations were held with members of the catalyst development groups at Cyanamid's Stamford Research Laboratories, to take advantage of their specialized knowledge in this field.

All hydrocarbon oxidations carried to completion in commercial practice are accomplished using an excess of air (oxygen). As a consequence, the literature references deal with stoichiometric quantities of hydrocarbons at most, not with fuel-rich systems. In the conceptual system, it will probably be desirable to run with some excess of fuel to increase oxygen conversion. An important part of the research done on catalytic oxidation of hydrocarbons has been directed toward the manufacture of commercially important chemicals, such as acrolein, or other partial oxidation products, as opposed to the ultimate products, carbon dioxide and water, desired in the present instance. For these reasons, the published literature was not directly applicable, although it did prove useful in considering the types of catalyst likely to perform well, and in planning the experimental approach to be adopted.

Among the hydrocarbons, olefins appear to be most readily oxidized, n-paraffins least readily, and aromatics intermediate. Among the paraffins, the short-chain compounds (methane, ethane, propane) yield the lowest oxidation rates^(3,4). It also appears that the relative efficiency of catalysts tends to be the same for a variety of hydrocarbons where complete combustion to carbon dioxide and water is involved⁽⁵⁾; thus, it should be possible to perform screening studies with a simple hydrocarbon system to rate a number of catalysts against each other. Silver has seen much use as a catalyst in studies of the oxidation of olefins, either to oxides such as ethylene oxide⁽⁶⁾ or (with higher olefin^h feed stocks) to carbon dioxide and water⁽⁷⁾. Higher olefins^h, when oxidized in the presence of vanadium pentoxide catalyst, tended to give intermediate oxidation products such as aldehydes and acids, and cuprous oxide has been much investigated as a catalyst for oxidative conversion of propylene to acrolein⁽⁷⁾. Some combustion processes result in substantial production of carbon monoxide, the further reaction of which is desirable as a means of consuming more free oxygen. Catalysts noted for utility in the low-temperature conversion of carbon monoxide to carbon dioxide include the oxides of copper, manganese, cobalt and silver, while oxides of other metals (e.g., iron and zinc) are cited for activity in the higher-temperature regime⁽⁸⁾. The selectivity of catalysts for specific reactions is illustrated by the fact that platinum and palladium catalyze the oxidation of hydrogen by air, subject to poisoning by carbon monoxide, while manganese dioxide catalyzes the selective oxidation of carbon monoxide by air in the presence of 100-1000 times the concentration of hydrogen⁽⁹⁾. Noble metals, specifically platinum and palladium, have long been known as active oxidation catalysts⁽¹⁰⁾, but their use has been limited to systems where the purification of feed stocks can be justified, or where it has been shown that feed gas compositions are such that the catalyst would be acceptably free of poisoning effects, and where activity or selectivity advantages outweigh the relatively high cost of these materials.

^hhigher molecular weight olefinic compounds

The carrier on which the active catalytic agent is supported is a very important consideration. The carrier can be designed and prepared to furnish a large exposed surface area over which the catalyst is distributed, thus contributing to initial high activity. In addition, a large surface area can assist in preventing loss of activity caused by sintering of catalyst crystallites crowded too closely together. Other functional benefits have also been observed(11).

Two approaches are commonly used in analyzing heterogeneous catalytic processes. One attempts to explain the reactions more or less fully, taking into account each of the steps, including bulk diffusion, pore diffusion, adsorption of reactants, mechanisms of surface reaction, and desorption of products. The last three of these are often looked upon as a single interrelated set of mechanisms (e.g. the Langmuir-Rideal and Langmuir-Hinshelwood models). This kind of technique yields basic information about the heterogeneous combustion process which is of great utility in predicting the effects of various scaleup parameters. The technique, however, requires the collection of large amounts of very precise data and a very complicated and time-consuming data analysis. Furthermore, the surface reaction models usually must be simplified to keep the number of unknowns to a reasonable level; this often results in poor data fits because the model does not represent the real system closely enough. The second approach consists of assuming that all the reaction parameters can be lumped together, and conversion can be treated as a function of contact time (with a pseudo-first order relationship) and temperature (using the standard Arrhenius form). This method is admittedly semiempirical, but agreement with experimental data over rather wide ranges is usually satisfactory. This technique has found great favor in industrial catalyst research, and was chosen for the catalyst studies performed in the present program.

b. Screening of Commercial Catalysts

(1) Selection of Candidates

Numerous catalysts are used commercially for oxidation processing. Examples of such catalysts are those used for oxidation of noxious automobile exhaust products, for conversion of sulfur dioxide to sulfur trioxide, ethylene to ethylene oxide, ammonia to nitric oxide, naphthalene to phthalic anhydride, and propylene to acrolein, among others. These possibilities were identified and considered during discussions with members of the catalyst research group at the Stamford Research Laboratories, and used as the basis for inquiries directed to major developers and/or producers of commercial catalysts. In describing the anticipated application conditions, care was taken to stipulate the projected use of stoichiometric or fuel-rich mixtures, and there was general recognition of the significance of this application feature. In addition to American Cyanamid Company, recommendations and samples were obtained from Davison Chemical Company (Division of W. R. Grace & Company), Engelhard Minerals and Chemicals Corporation, Girdler Catalysts Department (Division of Chemetron Corporation), and the Harshaw Chemical Company.

As a result of these inquiries and responses, twelve catalysts were selected for inclusion in the screening test program. These are identified and described in Table I, in which certain data gaps reflect a reluctance of the suppliers to publicize descriptive details.

TABLE I. COMMERCIAL CATALYSTS SELECTED FOR SCREENING TEST PROGRAM

Catalyst (1)	Active Compounds	Form and Size	Surface Area (3)	Normal Use
Code A (2)	proprietary (4)	1/16" x 1/8" extrudates	high	Automobile exhaust control
Code B	proprietary (4)	1/8" x 1/4" extrudates	high	Very low temperature water gas reaction
Code C	V ₂ O ₅ , K ₂ S ₂ O ₇	"Fluid" form, 70μ ave. dia.	high	Sulfuric acid, phthalic anhydride manufacture
Code D	Cu, Zn, Cr (calcined)	1/8" x 1/8" tablets	moderate	Moderate temperature water gas reaction
Code E	Cr ₂ O ₃ , Fe ₂ O ₃	1/8" x 1/8" tablets	moderate	High temperature water gas reaction
Code F (2)	proprietary (4)	1/8" x 1/8" tablets	moderate	Steam-hydrocarbon reforming
Codes G & H	V ₂ O ₅	1/8" x 1/8" tablets	high	Phthalic anhydride manufacture
Code I (2)	proprietary (4)	1/8" spheres	moderate	Hydrocarbon oxidation
Code J (2)	V ₂ O ₅	1/8" x 1/8" tablets	high	Hydrocarbon oxidation
Code K (2)	V ₂ O ₅	1/8" x 1/8" tablets	high	Hydrocarbon oxidation
Code L (2)	proprietary (4) (noble metal)	custom sized, honeycomb	moderate	Oxidation

(1) Identification of catalysts is available to qualified recipients from the Air Force Aero Propulsion Laboratory.

(2) Recommended by supplier.

(3) Defined as follows: low = <20 m²/g; moderate = 20-100 m²/g; high = >100 m²/g.

(4) Supplier chose not to publish this information.

(2) Methods

(a) General

A performance test capable of gaging the activity of candidate catalysts under temperature, pressure and composition conditions of interest was chosen as the main screening criterion. The test was established on a "bench" scale so that meaningful data could be obtained using small amounts of catalyst. In general, it was possible to carry out these tests so that performance features other than activity per se, such as ability to convert essentially all reacted fuel to carbon dioxide (CO_2), or tendency toward crumbling or dusting, might be observed.

(b) Test Apparatus

A schematic diagram of the test unit used for the screening tests appears as Figure 1. The reactor consisted of 1" I.D. Type 316 SS tubing 30" long, through the center of which ran a 3/16" O.D. x 27" long thermowell. The reactor diameter was chosen to provide the desired minimum radial space for catalyst, considering the expected range of catalyst grain size; a diameter greatly in excess of 1" would have caused large radial temperature gradients and required large quantities of catalyst. The length was chosen to permit study of the effects of variations in contact time and level of preheat, and the high conversions obtained with short beds of the active catalysts showed the length to be ample for screening purposes. Figure 1 shows a preheater capable of regulation to introduce the reactants at various temperatures. A metal coil exposed to the laboratory air was used to reduce the temperature of the exit gases in preparation for sampling and analysis. A Beckman Model 109A Hydrocarbon Analyzer and a Beckman Model 77700 Oxygen Analyzer were installed in-line to provide data on exit gas composition; in some of the runs, additional data were obtained by periodically withdrawing gas samples and subjecting them to infrared analysis. The furnace surrounding the reactor tube differed from the massive metal block commonly used to heat and maintain the temperature of tubular reactors. Such units provide relatively constant temperatures surrounding the reactor, but the thermal inertia is so large that warmups, cooldowns, and temperature adjustments consume long periods of time; e.g. it is hardly ever possible to collect data at more than one temperature on a given day. The furnace constructed for this program was fabricated using 0.5" thick-walled Type 304 SS tubing into which two external spiral grooves had been machined. Nichrome heating wire running through each of these grooves, and connected to separate control circuits, provided the means of temperature control. Although the mass of metal in the furnace tube was sufficient to provide reasonably uniform temperatures around the reactor, it was small enough to permit quite rapid temperature adjustments, e.g. 20-400°C. in a period of one hour. Thus, there was reasonable prospect of being able to get performance data at several temperatures in a given day.

With two exceptions, all catalysts listed in Table I were tested for activity in the above apparatus, using propane fuel and the gaseous feed system. In later tests with JP-7 and JP-4 fuels, the liquid feed fuel feed system was used. This comprised a metal blow case, a two-fluid atomizing nozzle, and a heated vaporization chamber. Flow of fuel to the nozzle was regulated by means of an indicating flowmeter and a precision needle valve.

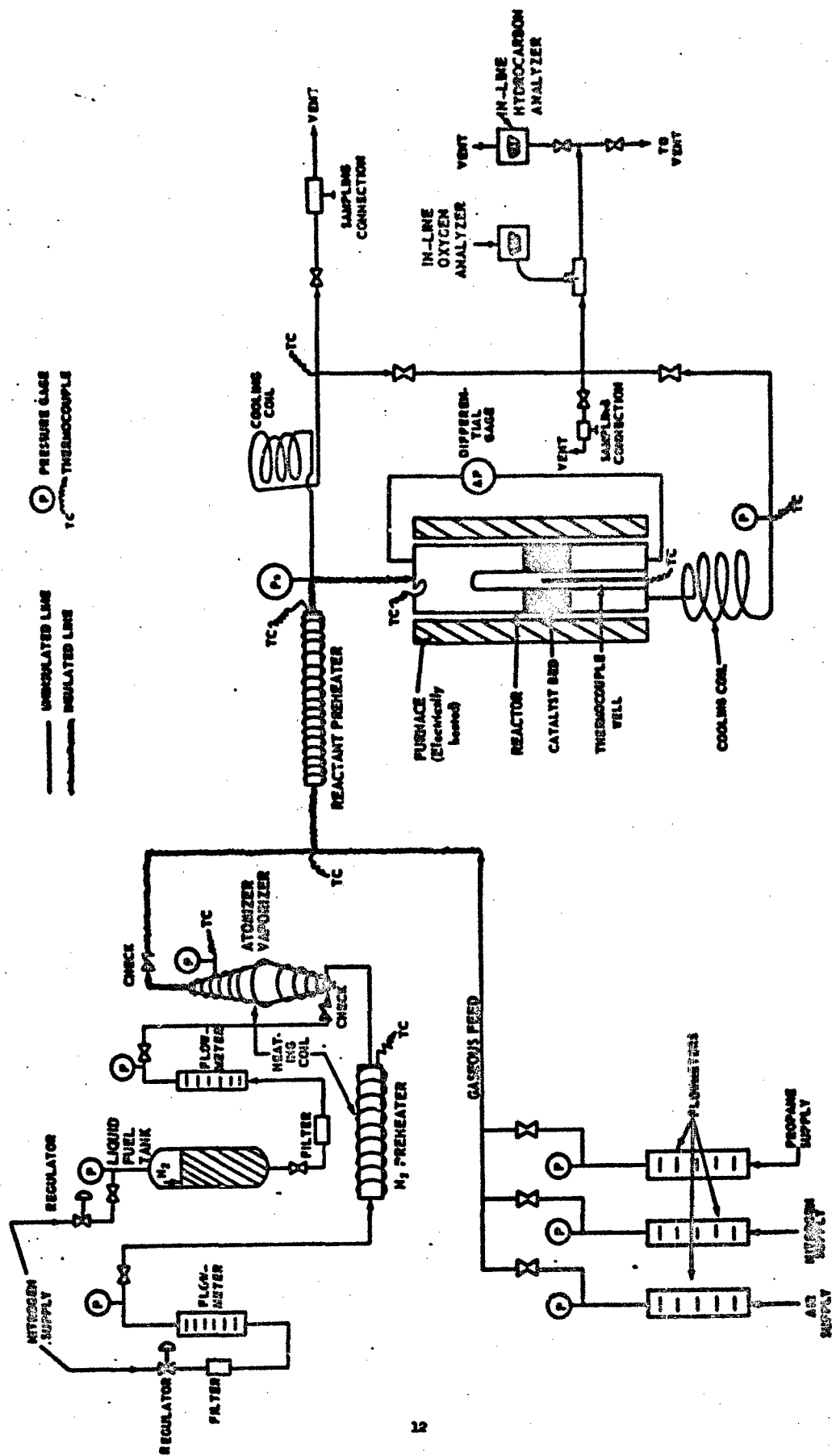


FIGURE 1. SCHEMATIC DIAGRAM OF CATALYTIC COMBUSTION TEST UNIT

Nitrogen was employed as the atomizing fluid, and a check valve guarded against the accidental backflow of air into the heated vaporization chamber. Whether feeding gaseous or liquid fuel, provision was made for dilution of the reactants with nitrogen, for reasons discussed below.

Difficulties were experienced in operating the oxygen analyzer during some of the screening runs. These difficulties were not encountered after Run CCP-14, following replacement of the sensing element. The hydrocarbon analyzer could not be used for liquid fuel runs (on either inlet or exit streams) because the instrument's measuring temperature was below the temperature of condensation of the fuel vapors.

(c) Test Procedure

The key to a workable screening test procedure lay in obtaining a proper proportion of diluent gas (nitrogen). At an excessive dilution, the flowing gas mixture dissipates too much of the heat of reaction, which presents difficulties in achieving and maintaining the catalyst temperature required for a given level of conversion. At very low dilution, the gases transport so little heat that high radial temperature differences develop within the bed, presenting a problem with overheating of the catalyst. The proper degree of dilution provides a tolerable rise in catalyst temperature above that of the surrounding furnace tube.

Experiments carried out using propane fuel and Code A catalyst to establish a standard level of dilution showed that a mixture containing 1.5% propane, 7.5% oxygen and 91% nitrogen was too rich. The maximum temperature at the center of the catalyst bed rose from approximately 400°C. to 1100°C. in less than 30 minutes. This rate of rise did not provide sufficient time, at any given temperature, to collect data representing catalyst performance. By decreasing the concentration of propane and oxygen to 0.75% and 3.75%, respectively, the rise time from 400°C. to 800°C. was increased to 1½-2 hours, and the maximum (hot spot) temperature could be readily controlled at the 800°C. level. This dilution level became the standard on screening tests made with propane fuel, and the following procedure was established.

- i. The oxygen analyzer and hydrocarbon analyzer were calibrated, using known samples.
- ii. A charge of fresh catalyst was weighed and placed in the reactor tube at a location well below the top of the heated section.
- iii. Nitrogen flow was directed through the reactor and catalyst, while the surrounding furnace was heated to a temperature approximately 50°C. below the expected "light-off" temperature, i.e. the temperature at which the reaction rate would be sufficient to carry the catalyst temperature above the furnace temperature.

- iv. While elevation of the furnace temperature continued, the flows of oxygen and propane in the stoichiometric ratio for complete oxidation were initiated, and temperatures were monitored in order to detect the light-off temperature. When this temperature was reached, the furnace was usually placed under automatic control to maintain a constant temperature.
- v. Periodic measurements were made of the oxygen and hydrocarbon content of the inlet and exit gases, and the temperature at various locations along the center axis of the bed. In some runs, samples of the exit gas were taken periodically for determination of % CO_2 , and various temperature, pressure and flow rate data were recorded.
- vi. Collection of data continued in this manner until the maximum catalyst temperature reached a predetermined upper limit, or until conversion reached essentially 100%. Then the gas streams were shut off in the order of propane, oxygen (air), and nitrogen.
- vii. The instruments were recalibrated.
- viii. When cool, the reactor tube was removed from the furnace and emptied of catalyst. The catalyst was examined visually and weighed for comparison with the initial weight charged.

In the liquid fuel runs made during the basic process studies, the same test procedure was employed, but care was taken during startup to insure the absence of residual fuel from a previous run. This was done by testing the exit gases for CO_2 while passing a mixture of nitrogen and air through the reactor as the furnace temperature was raised.

The propane used in these runs was c.p. grade, with minimum purity of 99%. The nitrogen was purchased in liquid form, and had a minimum purity of 99.9%. The air was obtained from a compressor, and passed through a separator, trap and filter before entering the test apparatus.

(3) Results

Screening test runs were made on all of the commercial catalysts listed in Table I, with two exceptions. The Code L catalyst was not tested because it was delivered so late in the program that to run it would have seriously disrupted other experimental studies requiring the same apparatus. The Code C catalyst was not tested because of its similarity to Code G and H catalysts. Conditions used in the screening tests are summarized in Table II; the space velocities ranged from 7,500 to 100,000 hr^{-1} , and the catalyst volume was either 15 or 25 cc. A 20% excess of fuel was used in the first 3 runs shown in the table; all others were carried out with the stoichiometric ratio.

TABLE II. SUMMARY OF RUN CONDITIONS, SCREENING TESTS WITH PROPANE FUEL

Run No.	CCP-	5	6	7	9	15	17	18	19	20	27
Total reaction time, hr.	2.0	5.15	2.33	2.50	2.25	4.50	3.0	2.0	4.0	2.75	
Catalyst type	Code E	Code A	Code D	Code F	Code I	Code J	Code J	Code J	Code B	Code M	
Catalyst, volume, cc.	25	25	25	25	15	25	25	25	25	15	
Flow rates, cc./min.											
Nitrogen (g)	10,900	11,100	11,100	7,500	10,850	10,850	10,850	10,850	10,850	20,350	
Air (g)	1,970	1,970	1,970	1,360	2,380	2,380	2,380	2,380	2,380	4,462	
Propane (g)	100	100	100	57	100	100	100	100	100	188	
Space velocity, hr. ⁻¹	31,100	31,600	31,600	21,800	53,200	31,900	31,900	53,200	31,900	100,000	
Reactor inlet temp., °C.											
Min.	187	187	205	303	222	252	254	245	160	280	
Max.	199	260	207	343	258	328	330	259	282	328	
Ave.	193	224	206	323	240	290	290	252	221	304	
Furnace temp., °C.											
Min.	295	306	332	531	307	375	423	388	206	360	
Max.	408	564	410	565	461	585	625	470	452	530	
Ave.	352	435	371	548	384	480	524	429	329	395	

Results obtained in the screening tests where significant conversion was observed are tabulated in Appendix A, Tables I-A through IX-A. Figures 2, 3 and 1-A through 6-A show clearly the effect of temperature on conversion in each case. In some of these tests, the combustion gases were sampled and analyzed for CO₂ content. This made possible the completion of a carbon balance, assuming all consumed oxygen to be accounted for by CO or CO₂. Calculated fractions of reacted propane converted to CO₂ as a function of conversion level are shown in Figures 4 and 5.

(4) Discussion

Of those catalysts tested, the Codes G & H catalysts proved to be inactive for this reaction at temperatures up to the supplier's maximum recommended values. All others showed significant activity. In the temperature-conversion curves, two conversion functions, oxygen in/oxygen out and \ln (oxygen in/oxygen out), are plotted on a log scale versus the reciprocal of the absolute "hot spot" temperature. The former should be a straight line if the reaction is overall second-order with respect to hydrocarbon, and the latter should be a straight line if the reaction is overall first-order. (This interpretation is developed in Appendix B.) In the present screening tests, it is inferred that the kinetics relate to the concentration of propane, since it has been observed previously⁽⁵⁾ that the oxidation of propane over many catalysts approximates first-order with respect to propane concentration and zero-order with respect to oxygen concentration. The curves indicate that a first-order kinetic relationship obtains for the combustion reaction(s) carried out in the presence of all but two of the catalysts. Catalyst D showed an overall second-order response, and Catalyst E showed fractional-order response.

Code A catalyst and Code F catalyst are revealed (Figures 2 and 3) to be the most active of all the catalysts tested, up to the maximum recommended temperature for each catalyst, or to an arbitrary maximum temperature of ~800°C. whichever is lower. The 800°C. temperature was selected as a maximum largely because it was known that some of the catalysts were sufficiently stable to remain active for long periods of time at that temperature. The use of lower temperatures would be preferred, in fact, as a means of lessening both the preheat requirements on startup and the heat exchange duty for cooling the combustor exit gases.

The initial sample of Code F catalyst consisted of 5/8" rings, which is the form in which it is normally used. To prepare it for test in our apparatus, the rings were crushed and sized to obtain a fraction of particles between 8 and 16 mesh (Tyler designation). Back pressure increased during the screening test, which was probably due to further mechanical breakdown of the catalyst granules, leading to clogging of flow channels. As a result, the maximum attainable flow was equivalent to a space velocity of only 21,800 hr.⁻¹. The data obtained (Table IV-A and Figure 3) indicated the Code F catalyst to have a much higher rate of increase of conversion with temperature than any of the other catalysts. However, there were technical difficulties during the test⁽¹²⁾, and the JP-7 fuel test results (Table X-A) with Code F catalyst in 1/8" x 1/8" tablet form are more meaningful inasmuch as no evidence of mechanical degradation was seen.

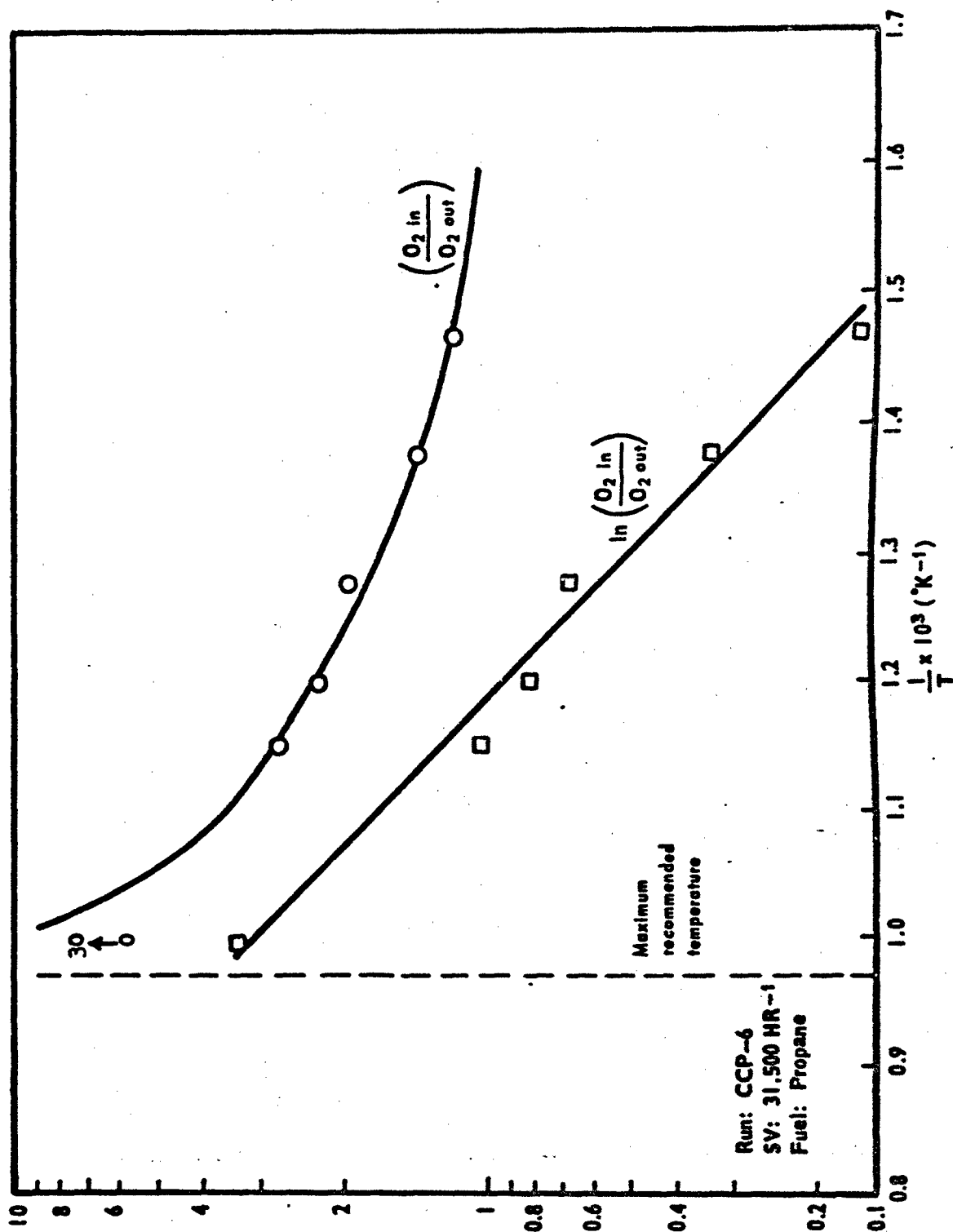


FIGURE 2. EFFECT OF TEMPERATURE ON OXYGEN CONVERSION, CODE A CATALYST

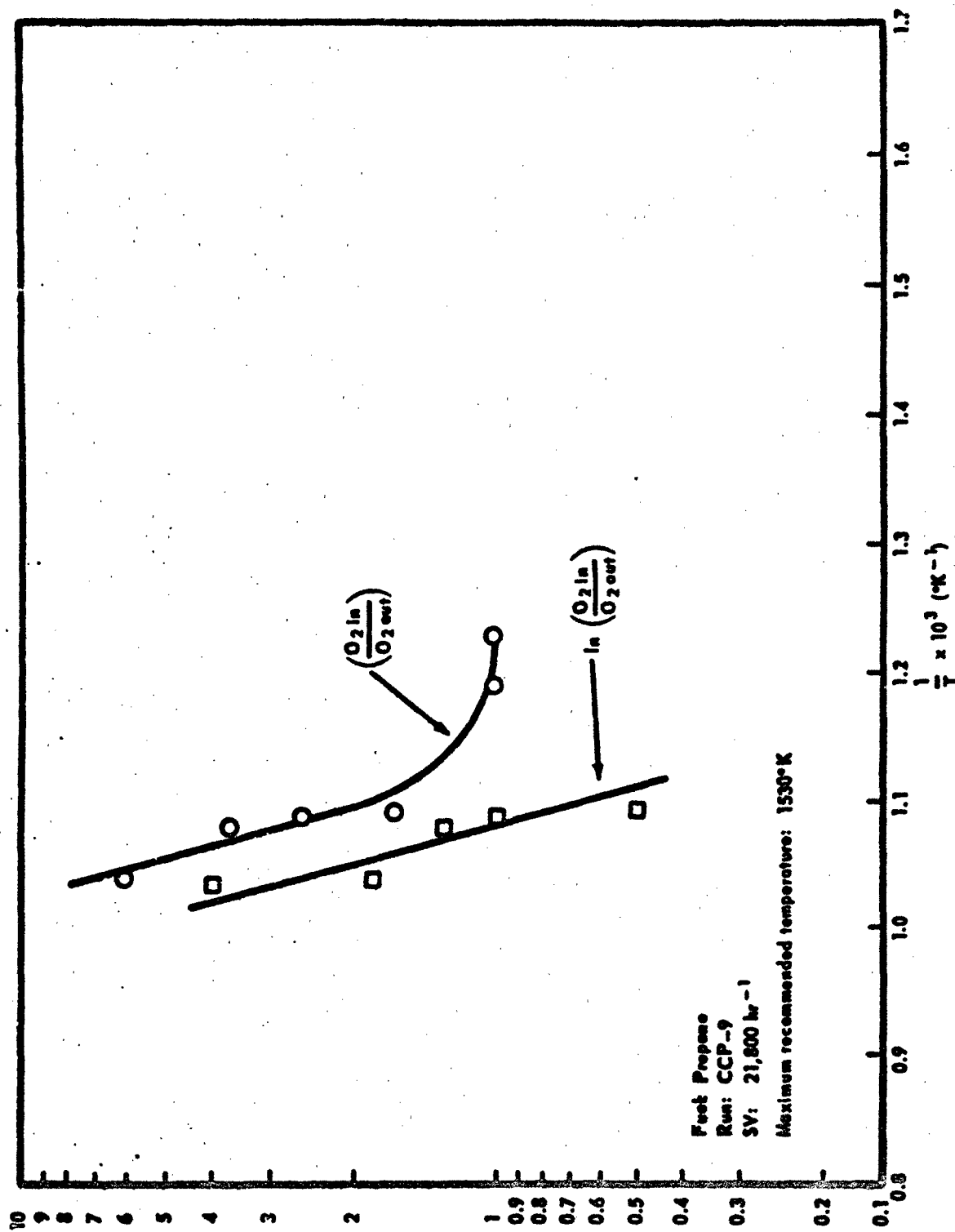


FIGURE 3. CODE F CATALYST - EFFECT OF TEMPERATURE ON OXYGEN CONVERSION

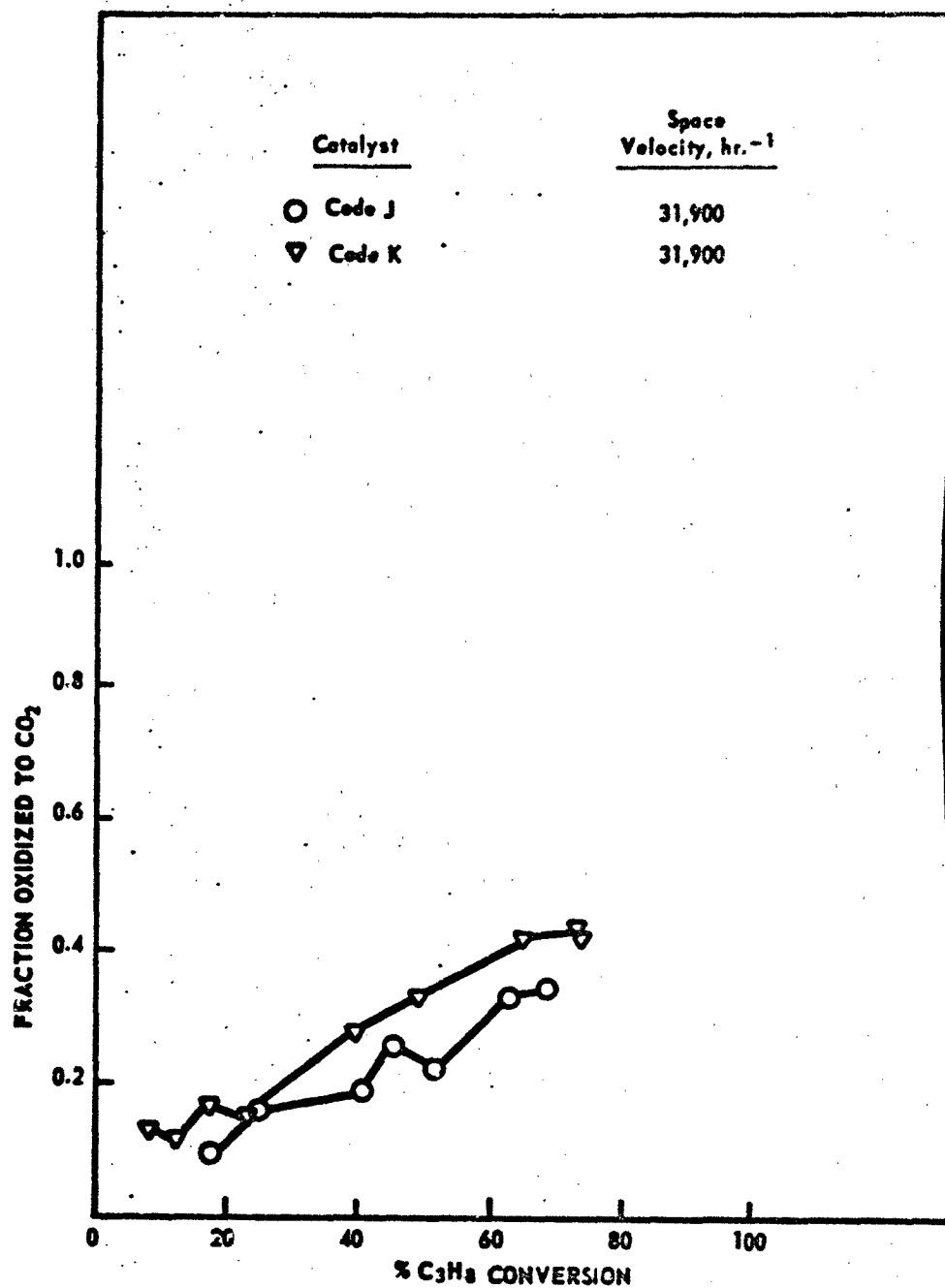


FIGURE 4. EFFECT OF CONVERSION LEVEL ON THE FRACTION OF CONSUMED PROPANE OXIDIZED TO CARBON DIOXIDE

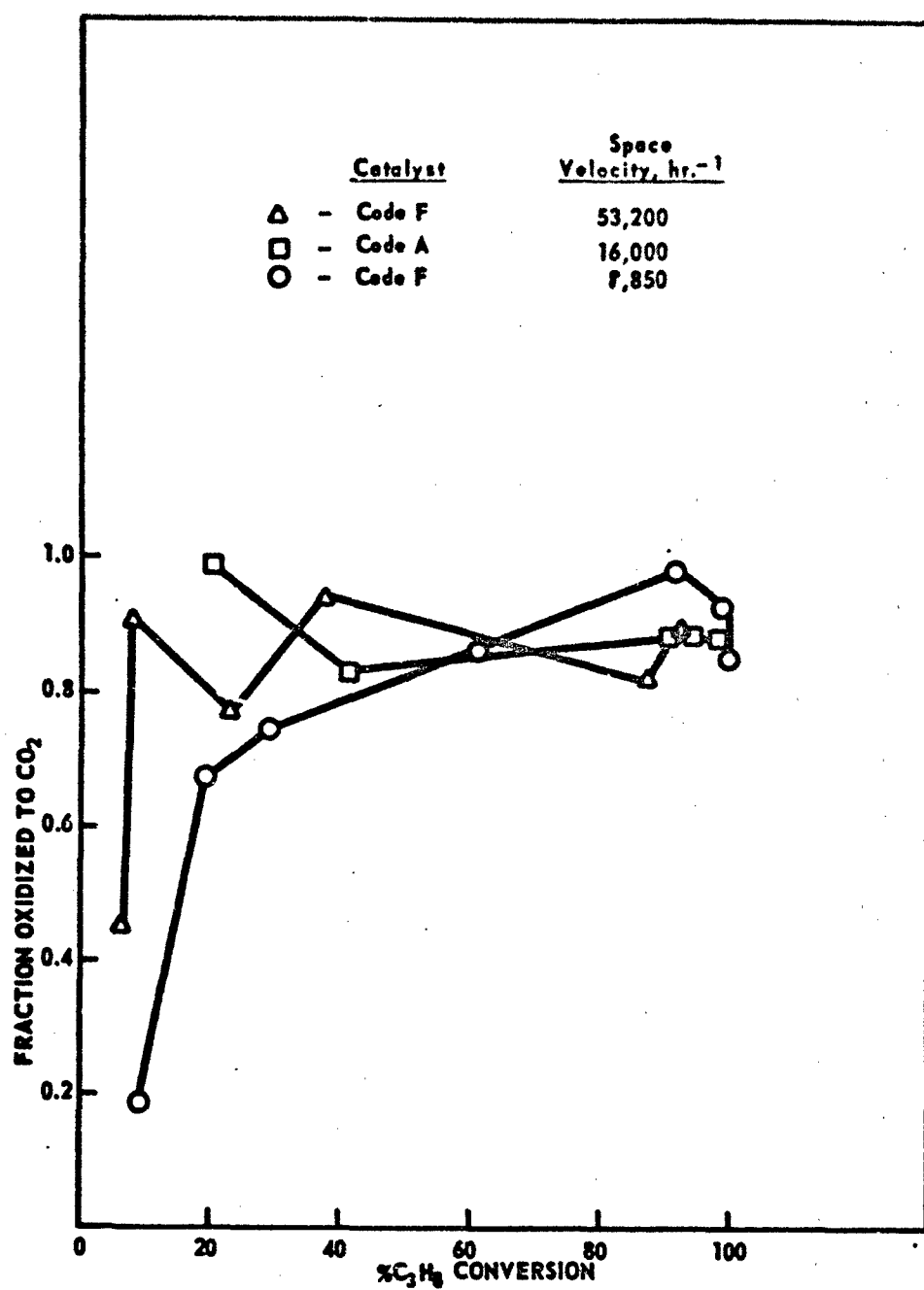


FIGURE 5. EFFECT OF CONVERSION LEVEL ON THE FRACTION OF PROPANE OXIDIZED TO CARBON DIOXIDE

These are more closely comparable with results obtained with jet fuel over Catalyst A at the same space velocity. The comparison is shown in Figure 14, where it is seen that Catalyst A is more active. For a more rigorous comparison, catalyst size and shape should be identical.

Differences in CO_2/CO distribution in the exit gases are significant because of their effects on the amount of free oxygen converted per unit quantity of fuel burned, and associated heat and volume (pressure) effects. The plots in Figures 4 and 5 show that the Code A and Code F catalysts are characterized by high conversion of CO to CO_2 . The low conversion over Codes J and K catalysts is in line with the experience of others using V_2O_5 catalysts⁽⁷⁾.

Aside from features already mentioned, the various catalysts tested in the screening program did not exhibit any other distinguishing characteristics.

c. Screening of New Catalysts

(1) General

A catalyst that had not yet reached commercial status was tested. This formulation indicated it might provide higher thermal stability with little penalty in initial activity. The catalyst designated Catalyst M, was given a screening test at a space velocity of $100,000 \text{ hr}^{-1}$ using a stoichiometric mixture and propane fuel. Run conditions are given in Table II (CCP-27).

(2) Results and Interpretation

Data obtained for the screening test using Code M catalyst are summarized in Appendix Table XI-A. A conversion of 30% was obtained at the maximum furnace temperature (525°C .), giving an exotherm of about 80°C . at the "hot spot" location. Figure 7, where data for regular Code A catalyst at several space velocities are plotted, shows several points from the run with Code M, indicating lower activity for propane oxidation. Unfortunately, time did not permit further testing under directly comparable conditions.

d. Basic Process Studies

(1) General

A selection of catalysts was made based on the screening test results, in order that work under this task of the program might be concentrated on one or two catalysts. Code A and Code F catalysts were selected for the process studies. All experimental work was conducted using the test apparatus described previously (Figure 1). Most of these studies were made using propane and JP-7 fuels. Some tests on Catalyst A were carried out using a JP-4 fuel representative of MIL-T-5161G specification, which is about as low in quality as JP-4 can be.

The following discussion indicates several areas in which additional study is advisable, but could not be undertaken as a part of the present program due to demands for manpower and apparatus on other essential tasks in the program.

(2) Results and Discussion

(a) Space Velocity

The effect on catalyst performance of changes in space velocity was studied simply by adjusting the total flow of inlet gas to the catalytic reactor. Except where the effects of variations in reactant ratio were the subject of study, these runs were made at the stoichiometric ratio. The accuracy of the reaction rate constants calculated therefrom was not as high as can be obtained in the laboratory because significant (unmeasured) radial temperature gradients existed in the catalyst bed. However, the uniform treatment of the data in these tests did yield rate constants of value for conceptual design studies. The rate constant at any given temperature was calculated from the run data, assuming that the entire charge of catalyst was at this temperature; in reality it was the maximum temperature measured in the central thermowell.

The first part of this discussion is confined to tests made with propane as fuel. The effect on Code F catalyst performance of variations in space velocity was investigated in two runs. Conditions are summarized in Table III, data in Tables XII-A and XIII-A in Appendix A, and the first-order data plots are given in Figure 6. Similar information was obtained for Code A catalyst, see Runs CCP-6, 8 and 23 in Tables II and III for conditions, Tables II-A, XIV-A and XV-A for data summaries, and Figure 7 for plots of the data.

A discussion of Code F catalyst results is of doubtful value because of the undetermined amount of dusting or crumbling which took place⁽¹²⁾. Catalyst A data are more reliable in this respect. The plots in Figure 7 indicate a non-linear response of conversion to space velocity at a given temperature in the space velocity (SV) span of 16,000 to 53,000 hr.⁻¹. Additional data are needed before this can be interpreted in terms of the catalyst and operating characteristics for propane fuel. It is possible that additional information on temperature profiles in the radial direction would help to account for the apparent non-linear response.

A number of runs were made with JP-7 fuel over Code A catalyst, using stoichiometric mixtures at various space velocities in the range of 32,000-150,000 hr.⁻¹, and these provided the basis for calculation of the reaction rate constant using the Arrhenius equation. The run conditions are summarized in Table IV, see JT-4, JT-5, JT-6A and JT-6B. The calculation method is described in Appendix C. Results at 725°C. are as follows:

TABLE III. SUMMARY OF RUN CONDITIONS, PROCESS STUDIES WITH PROPANE FUEL

Run No.	CCP-	8	22	23	24	26	28	FIM-1A	FIM-1B
Total reaction time, hr.	2.25	2.0	2.83	3.0	1.25	2.50	1.50	1.0	1.0
Catalyst type	Code A	Code F	Code A	Code F	Code A	Code A	Code A	Code A	Code A
Catalyst volume, cc.	15	50	50	50	25	25	25	25	25
Flow rates, cc./min.									
Nitrogen (g)	11,100	10,850	10,850	6,000	10,850	10,850	0	0	0
Air (g)	1,970	2,380	2,380	1,320	2,380	2,380	26,334	13,167	13,167
Propane (g)	100	100	100	51	100	100	266	133	133
Space velocity, hr. ⁻¹	53,200	16,000	16,000	8,850	31,900	31,900	63,800	31,900	31,900
Reactor inlet temp., °C.									
Min.	243	222	194	125	208	204	183	147	147
Max.	286	246	258	223	260	252	249	235	235
Ave.	265	233	226	174	234	228	216	191	191
Furnace temp., °C.									
Min.	357	376	320	209	287	290	249	260	260
Max.	495	404	466	369	449	466	435	390	390
Ave.	426	390	393	289	368	378	342	325	325

^a oxygen in 315% excess of stoichiometric ratio

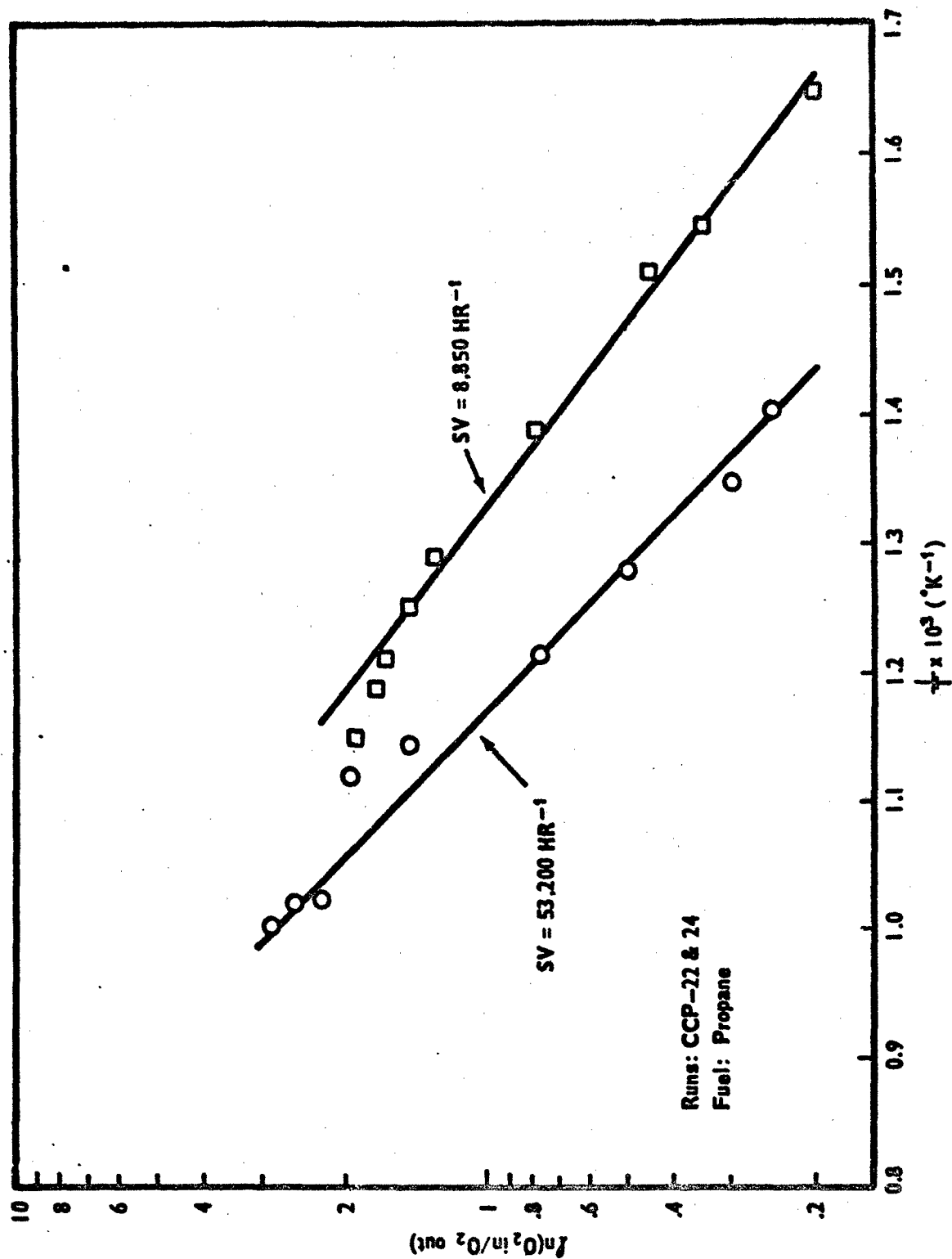


FIGURE 6. EFFECT OF SPACE VELOCITY ON TEMPERATURE RESPONSE OF CODE F CATALYST

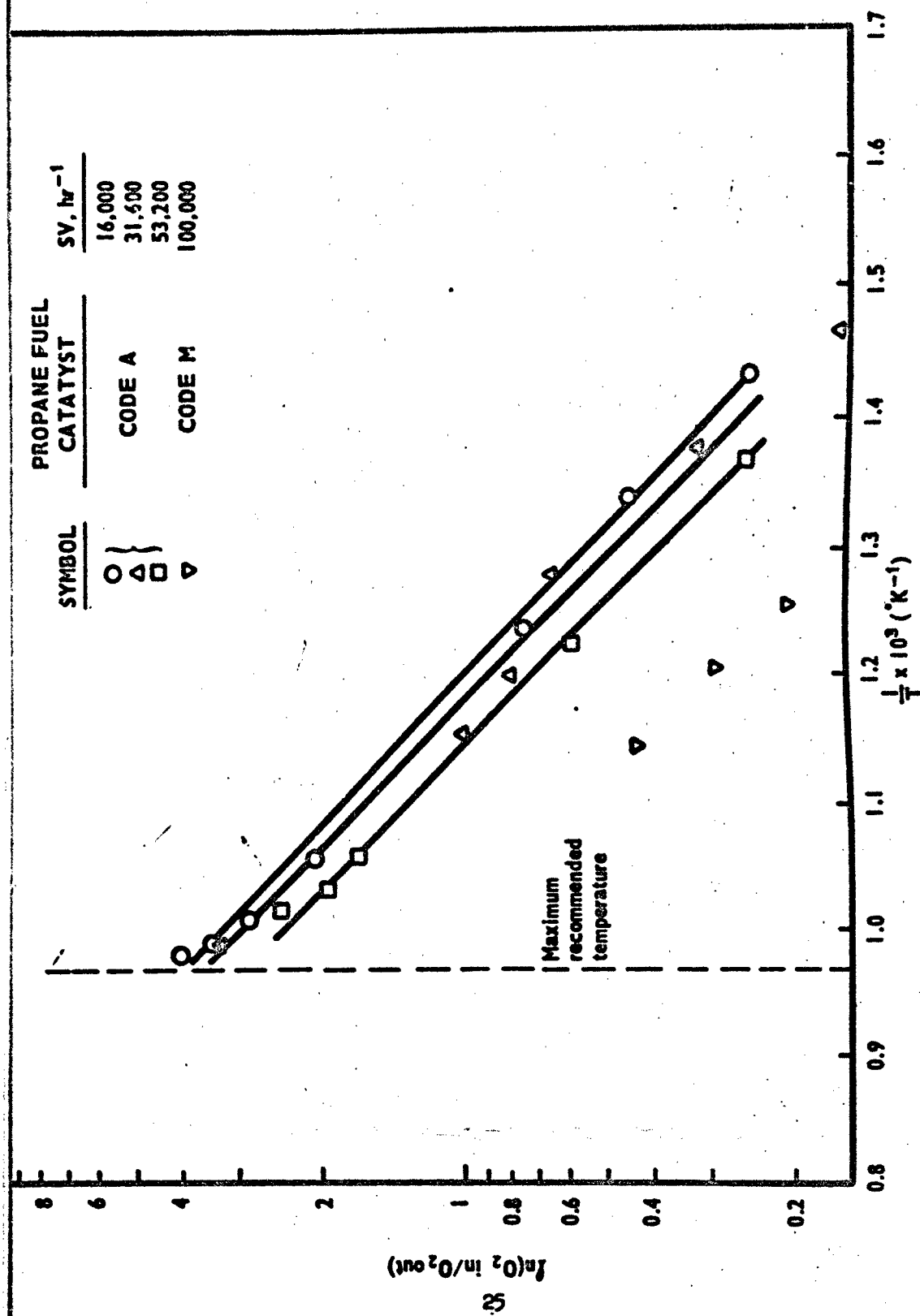


FIGURE 7. EFFECT OF SPACE VELOCITY ON TEMPERATURE RESPONSE OF CODE A AND M CATALYSTS

TABLE IV. SUMMARY OF RUN CONDITIONS, STUDIES WITH JP-7 FUEL

Run No.	JT-	2	4	5	6A	6B	7	8	9
Total reaction time, hr.		4.75	3.5	3	3	0.5	4	1.67	3.5
Catalyst type		Code A	Code A	Code A	Code A	Code A	Code A	Code P	Code P
Catalyst volume, cc.		25	15	25	25	25	25	25	25
Flow rates, cc./min.									
Nitrogen (g)		10,890	10,890	34,200	55,050	34,200	34,200	22,950	34,200
Air (g)		2,380	2,380	7,450	7,450	7,450	7,450	4,800	7,450
JP-7 (l)		0.248	0.248	0.776	0.776	0.776	1,552	0.500	0.776
Space velocity, hr. ⁻¹ (equivalent weight of propane)		32,000	53,200	100,000	150,000	100,000	100,000	66,700	100,000
Reactor inlet temp., °C.									
Min.		155	147	159	147	172	110	174	209
Max.		201	159	181	197	184	184	184	271
Av.		178	153	170	172	178	147	179	240
Furnace temp., C.									
Min.		230	290	234	285	410	250	319	240
Max.		478	444	550	497	470	534	497	510
Ave.		349	367	392	391	440	392	403	375
Feed press (Ps), psig									
Min.		1.0	4.0	13.0	26.5	18.0	13.0	23.0	13.0
Max.		1.25	5.5	18.5	32.5	18.25	20.0	28.0	19.3
Ave.		1.125	4.75	15.75	29.5	18.125	16.5	25.5	16.15
Δ P, reactor, psi									
Min.		0.426	0.474	2.015	2.76	2.48	2.155	0.56	1.51
Max.		0.774	0.678	2.900	3.40	2.92	3.195	0.628	1.85
Av.		0.600	0.576	2.458	3.08	2.70	2.675	0.594	1.68

<u>Run Number</u>	<u>SV (hr⁻¹)</u>	<u>K (vol. gas³/vol. cat.-hr.)</u>
JT-4	53,300	142,000
JT-5	100,000	143,000
JT-6A	150,000	194,000
JT-6B	100,000	143,000

The highest of these values was chosen as a basis for design calculations. This choice is conservative because there is evidence [Section III-2-f-(1)] that the contemplated use of excess fuel will provide higher oxygen conversion. Also, one can expect to design an operational bed in which a greater portion of the catalyst is maintained close to the desired temperature. The bed temperature of 725°C. was chosen because the supplier of Catalyst A advised that this catalyst had been found to have satisfactory thermal stability at that level.

The design rate constant was in quite good agreement with the constant determined experimentally with a stoichiometric mixture of JP-4 fuel and oxygen, using a charge of diluted Catalyst A that had been used previously for the 60-hour run with various excesses of JP-4 (see Table V). Data for the rate constant determination are shown in Table XXXII-A, Appendix A. Graphical interpretation of these data yield a value of 218,000 hr⁻¹ for K, the reaction rate constant. The fact that the reactor pressure in this run reached 32 psia may explain why the value is about 13% higher than the design value (see below).

(b) System Pressure

An attempt was made to evaluate the effect of system pressure on the performance of Code A catalyst with propane fuel. It proved unsuccessful due to the lack of reliable pressure data. The pressure effect was evaluated only in the case of liquid fuel and Code A catalyst, and over the range of 0.5 to 15 psig, using the stoichiometric fuel-air mixture. In these studies, system pressure was estimated at the midpoint of the catalyst bed using readings from gages in the entrance and exit lines, and allowing for the relative amounts of inert ceramic beads packed above and below the catalyst bed. Run conditions are given in Table IV (see Runs JT-2, 5 and 6A), and results were used to calculate reaction rate constants under actual reaction conditions. The results of these calculations are given in Figure 8, where T_R and P_R represent the "hot spot" temperature (°K) and the pressure (psia) existing at the center of the catalyst bed. All of these runs yielded data points at 600°C., and a comparison of the rate constants at that temperature was made.

<u>Run Number</u>	<u>Reaction pressure, psia</u>	<u>K, ($\frac{\text{cu. ft. gas}^3}{\text{cu. ft. cat.-sec.}}$)</u>
JT-2	15.2	30.4
JT-5	21.7	51.1
JT-6A	29.1	53.0

³volume includes volume of fuel vapor

TABLE V. SUMMARY OF RUN CONDITIONS, 60 cc TEST WITH MEL-T-51610 FUEL

On-stream (2) Hours		Catalyst: Code A, diluted (1)												Space Velocity: 100,000 hr ⁻¹											
		0-2.5		2.5-4.7		4.7-5.0		5.0-8.9		8.9-9.5		9.5-11.7		11.7-12.0		12.0-15.7		15.7-19.1		19.1-24.2		24.2-28.3		28.3-31.3	
Operation:		Start-up		Test		Start-up		Test		Start-up		Test		Start-up		Test		Start-up		Test		Start-up		Test	
Cum. Test Hours (3)		0		2.8		2.8		6.1		6.1		8.3		8.3		15.0		15.0		20.1		20.1		28.1	
Flow Rates:																									
Fuel, cc/min (liquid)		1.5 (est)		27.4		27.4		27.4		27.4		27.4		27.4		27.4		27.4		27.4		27.4		27.4	
Nitrogen (total) l/min (gas)		8.9		8.9		8.9		8.9		8.9		8.9		8.9		8.9		8.9		8.9		8.9		8.9	
Air l/min (gas)																									
Fuel Excess, %		Variable		est 400		est 400		210		210		130		130		95		95		45		45			
Temperature, °C																									
Reactor Inlet, high		211		212		-		202		-		190		212		196		-		209		199		241	
" " , low		202		210		-		150		-		186		195		185		-		194		186		199	
" " , ave.		208		211		-		186		-		188		204		192		-		198		192		224	
Furnace high		440		492		-		460		-		463		-		494		-		496		481		534	
" low		311		479		-		305		-		463		-		460		-		359		330		524	
" , ave.		356		484		-		443		-		467		-		482		-		469		447		535	
Hot Spot-high		628		760		-		723		-		742		790		747		690		752		698		780	
" low		320		709		-		640		-		704		970		684		-		970		913		146	
" , ave.		454		727		-		691		-		732		660		726		-		709		627		704	
Combustor Press, psig ave.		25.8		30.0		-		28.1		-		29.4		26.7		30.1		33.1		24.5		23.6		26.1	
Bed Press Drop, psi ave.		2.39		2.94		-		2.88		-		2.90		3.19		3.21		2.3		3.42		3.11		3.83	

Notes:

- (1) 30 cc catalyst mixed with 60 cc ceramic
- (2) Total exposure time to fuel, regardless of conversion
- (3) Time after a 90% or better conversion was initiated, includes short intervals at lower conversion
- (4) Increased flow due to operational error

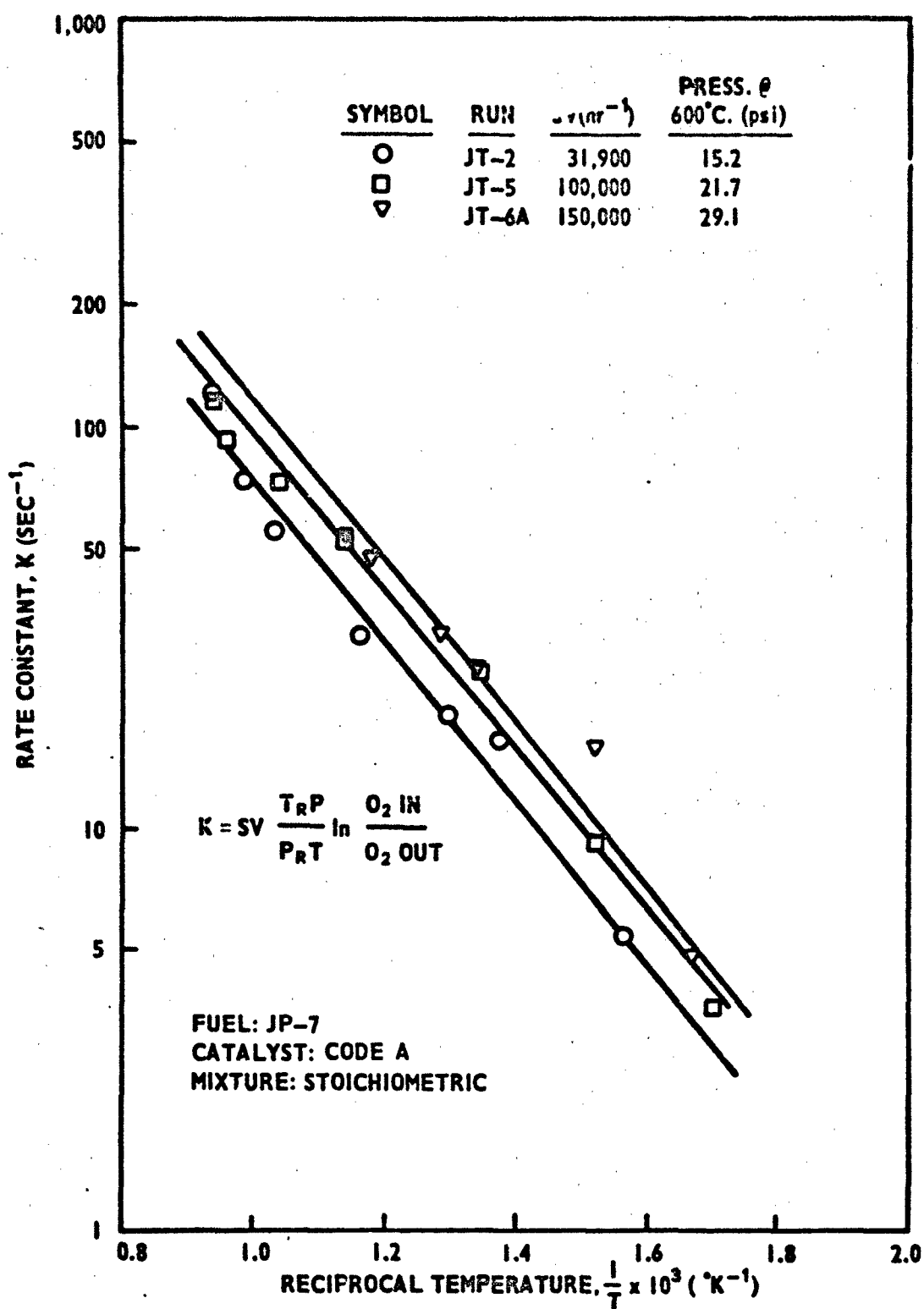


FIGURE 8. EFFECT OF RUN CONDITIONS ON REACTION RATE CONSTANT

The above findings indicate an increase in the rate constant with increasing system pressure. It would be useful to study the subject further in tests where system pressure is varied independent of space velocity, the effects of varying catalyst grain size are evaluated, and the pressure regime is extended below one atmosphere.

(c) Catalyst Grain Size

This study was confined to Code A catalyst. Although all performance runs were made using the same size Catalyst A ($1/16$ " dia. x $1/8$ " average length), the effect of particle size on pressure drop was determined at two levels by measurements made while passing air at room temperature through the reactor tube. A differential pressure gage (Wallace and Tiernan Model FA141) connected to pressure taps in the top and bottom end closures of the reactor tube was used. In addition to the grain size given above, Catalyst A with $1/32$ " dia. x $1/16$ " average length was tested. Blank data representing the reactor tube and catalyst bed support internals were collected so that data for the catalyst bed only could be obtained by difference. The results are shown in Figure 9.

Because there is a volume increase associated with the complete oxidation reaction, it may be expected that this effect (in addition to normal thermal expansion) will cause a significant response in pressure drop across the bed as conversion level increases. Such is indicated in Figure 10, plotted from data taken in Runs JT-2 and JT-4.

(d) Temperature Profile

Data were obtained by thermocouple traverse in the central thermowell, during all runs, to locate the maximum, or "hot spot", temperature. The amount of exotherm was influenced by the extent of reaction and other factors, as indicated by data taken under differing conditions. One run was made, using propane as fuel, in which the Code A catalyst charge was diluted uniformly with inert ceramic beads in the ratio of two parts (volume) of beads to one part of catalyst. Run conditions are given in Table VI (see Run CT-2). This run produced a series of temperature profiles along the center axis of the catalyst bed, which are shown in Figure 11. Table IV and Figure 12 give corresponding information for a run in which undiluted catalyst and JP-7 fuel were employed. See also data in Table V and Figure 21 pertaining to tests with JP-4 fuel.

The curves in Figure 12 show that the exotherm, even when operating with substantial nitrogen diluent, was in the vicinity of 350°C . at the central thermowell. When the catalyst was diluted (Figures 11 and 21), the exotherm measured from point of inflection was more manageable, ranging from 250°C . to 320°C . depending upon conditions in the run. Some shifting can be detected, resulting from changes in composition, space velocity and preheat condition. One of the significant aspects of profile control is the effect of "hot spots" on the stability of catalyst activity. During the useful lifetime of a catalyst bed, the point of maximum reaction (and temperature buildup) will shift from one location to another, until large portions of the bed have become thermally deactivated to about the same degree. Superimposed on this pattern of deactivation would be the temporary loss of activity, through coke deposition, and the restoration which takes place via regeneration.

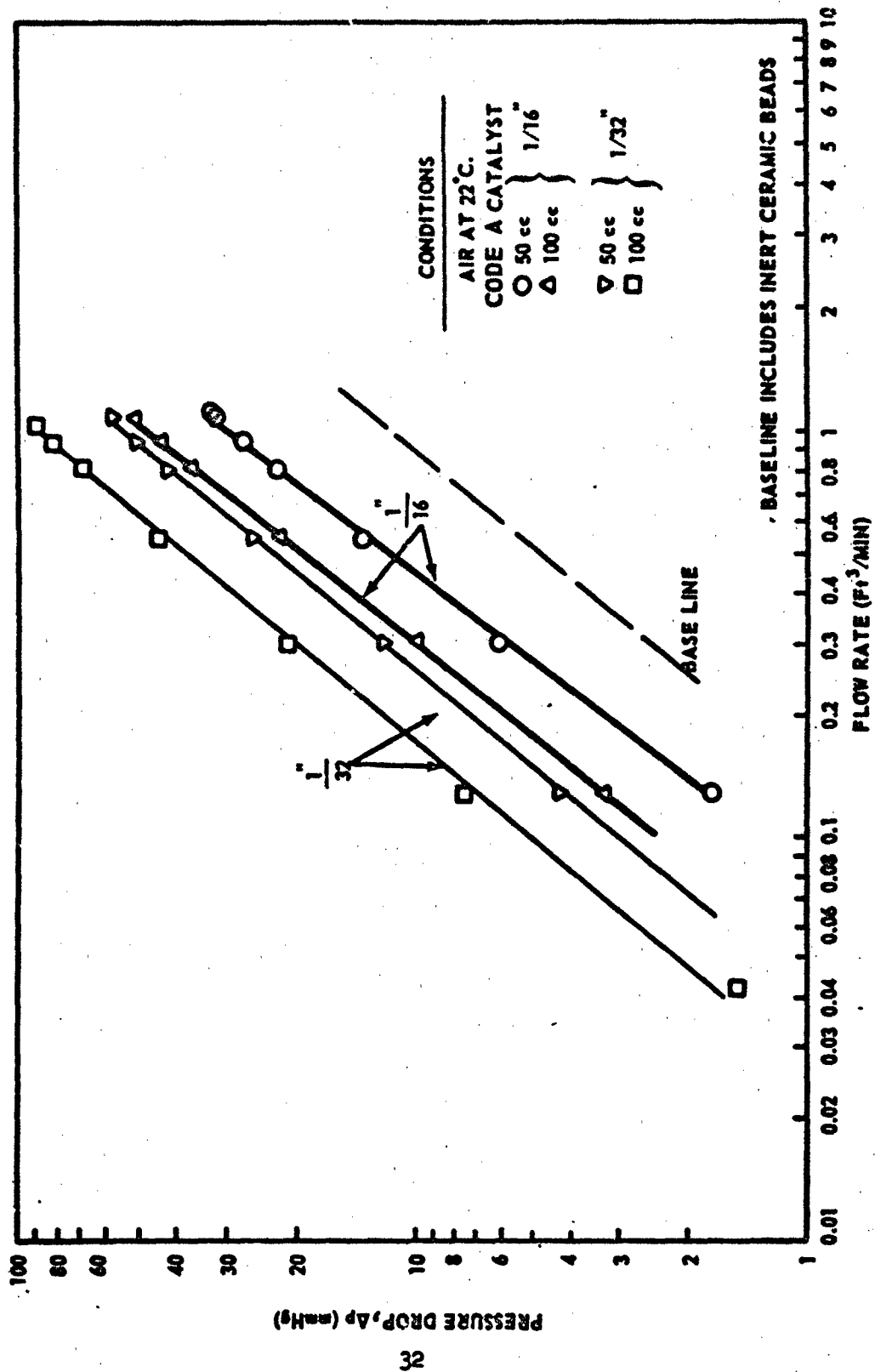


FIGURE 9. EFFECT OF BED THICKNESS ON RESISTANCE TO FLOW

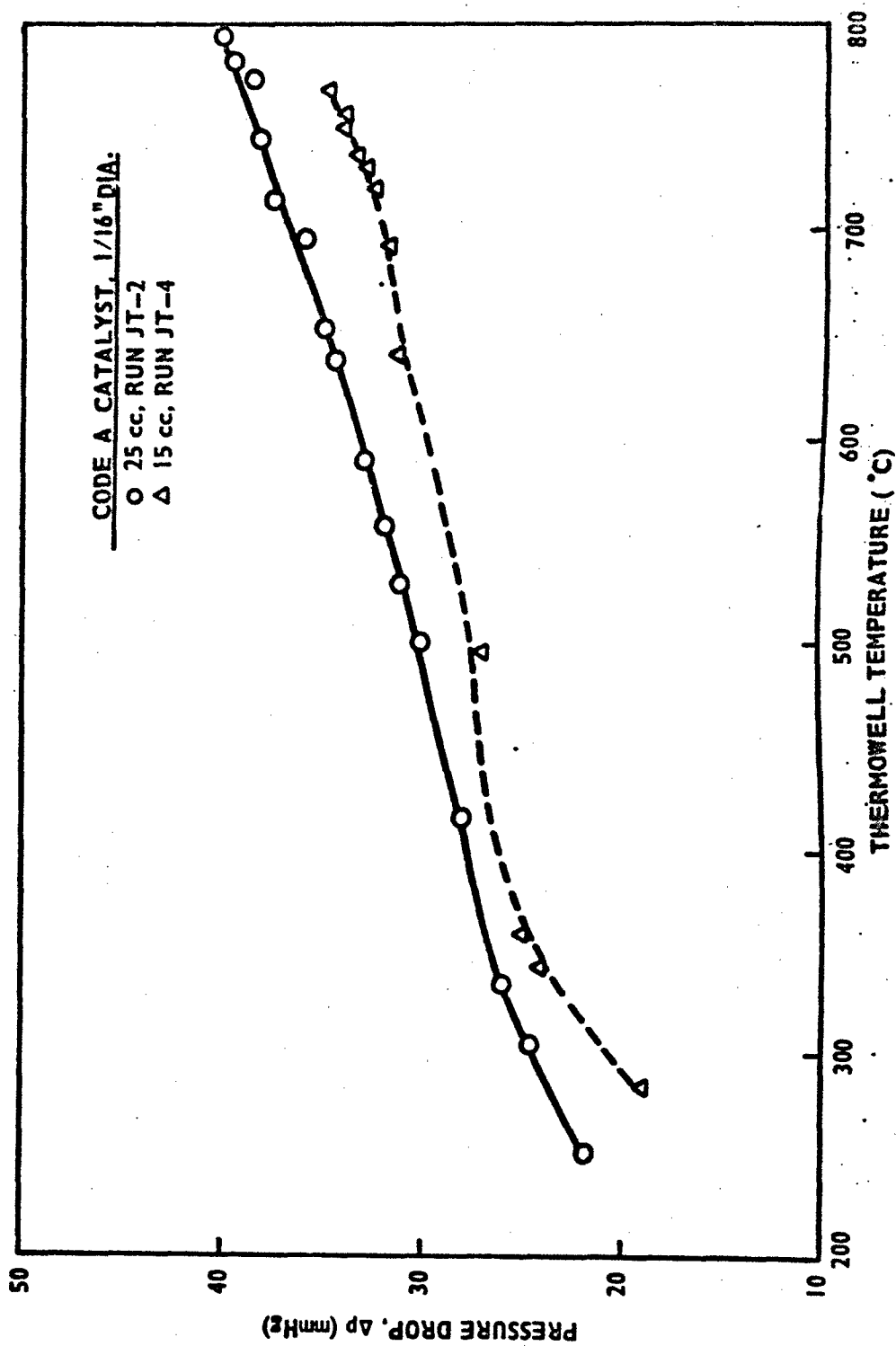


FIGURE 10. PRESSURE DROP AS AFFECTED BY REACTION CONDITIONS

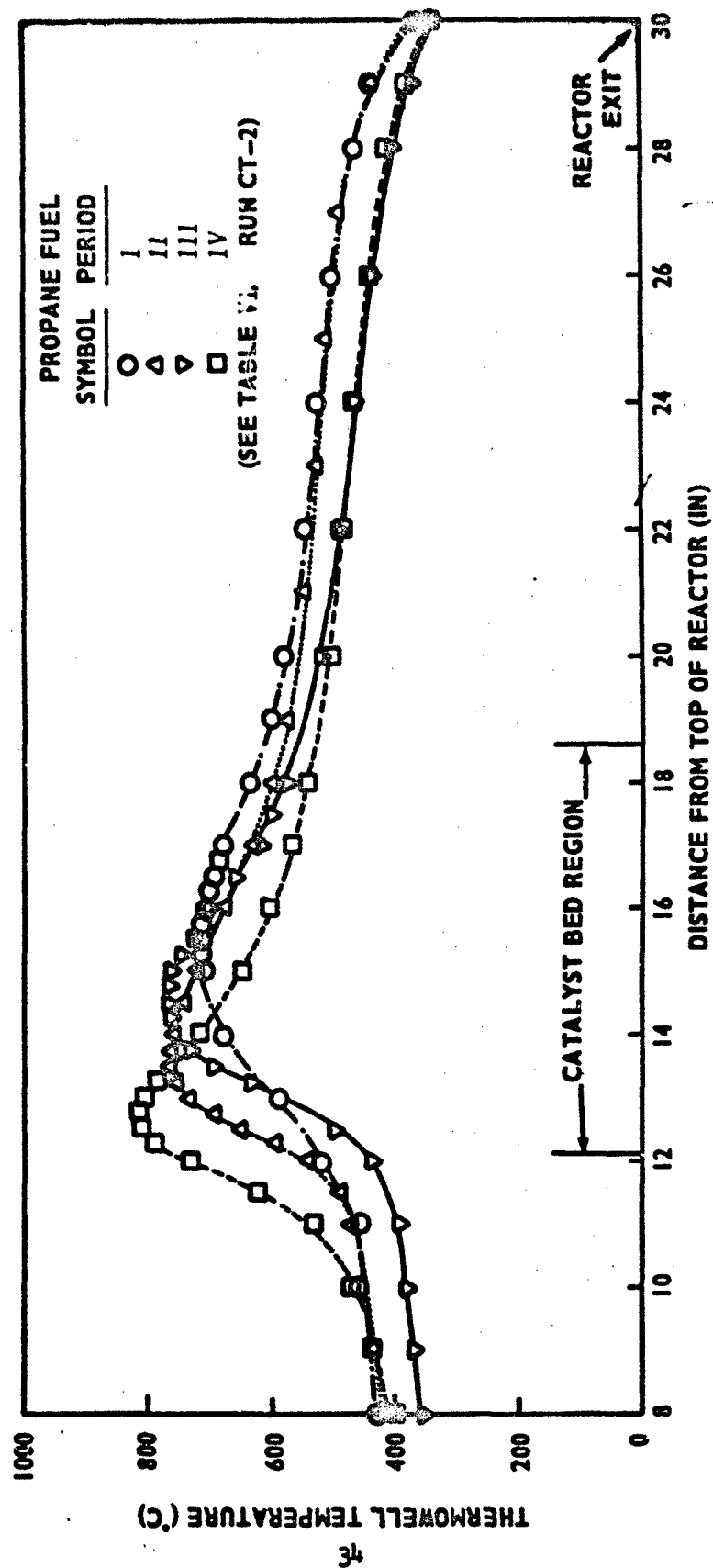


FIGURE 11. BED TEMPERATURE PROFILES DURING EXTENDED RUN WITH DILUTED CODE A CATALYST

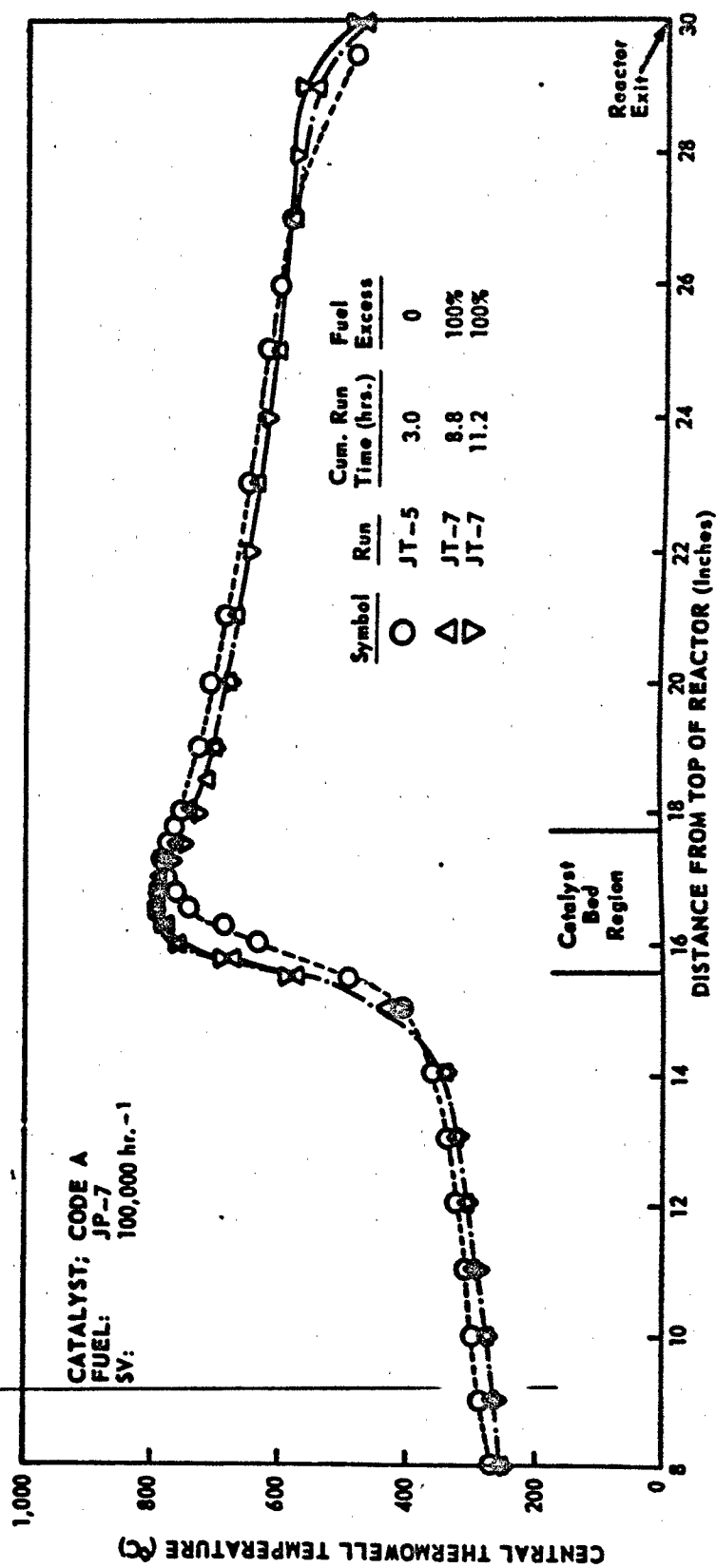


FIGURE 12. EFFECT OF CUMULATIVE RUN TIME AND EXCESS FUEL ON REACTOR TEMPERATURE PROFILE

e. Effect of Fuel Composition

(1) General

As stated above (III-2-a), the relative activities of catalysts for the oxidation of various hydrocarbons can generally be predicted if one knows the relative activity for just one type of hydrocarbon. However, testing of performance with military jet fuels was specified as a part of the investigation to be made using catalysts chosen as a result of the screening program. Through consultation with the Technical Project Engineer, JP-7 was selected as the first priority fuel for this purpose. A sample of JP-7 was furnished from the Aero Propulsion Laboratory at Wright-Patterson Air Force Base, along with the typical properties appearing in Table XXXIII-A. To augment this information, a portion of the JP-7 sample was analyzed for sulfur, carbon and hydrogen content. The results were as follows:

Sulfur content, % wt.	none found ²
Composition:	
carbon, % wt.	84.3
hydrogen, % wt.	15.7

The Aero Propulsion Laboratory also provided samples of JP-4 fuel representative of MIL-T-5161G quality. The inspection data are given in Table XXXIII-A. It can be seen that this fuel differs substantially from typical JP-7. The aromatics content is close to the maximum permitted in JP-4, and the data otherwise indicate a relatively low-quality fuel.

In order to operate the 1" tubular reactor with liquid fuel, the liquid feed system shown in Figure 1 was installed and tested. This provided for pressure-feeding of the fuel through a filter and meter to an atomizing nozzle at the base of a heated vaporizing chamber. Hot nitrogen was supplied to the nozzle as the atomizing fluid. The mixture of nitrogen and fuel vapors was next passed through a heated line to a position near the preheater where the air supply (and more nitrogen) was introduced. A check valve prevented backflow of oxygen-containing gases into the vaporizing chamber. In general, this system functioned satisfactorily, but fluctuations were encountered that required close attention to maintain a desired flow rate in the range of 15 to 100 cc/hr.

Unreacted liquid fuel present in the reactor exit gases condensed in the line as the gases were cooled as required for delivery to the in-line analytical instruments. The hydrocarbon analyzer did not function on liquid fuel runs; therefore, carbon balances were computed only on propane runs.

²by bomb combustion and turbidimetry, sensitive to 25 ppm.

(2) Tests and Results

The various runs made using JP-7 fuel were carried out under conditions summarized in Table IV. The test conditions for JP-4 fuel are given in Table V. The purposes of these runs, and the results obtained are discussed hereinafter.

(a) Space Velocity and Temperature Effects

Runs JT-2 and JT-4 (see Table IV) were conducted over Code A catalyst at JP-7 mass flow rates calculated to match those used in earlier propane runs made with standard nitrogen dilution and at the space velocities shown in the table. Tables XVI-A and XVII-A (see Appendix A) give summaries of the data obtained, and Figures 8-A and 9-A give the temperature vs conversion plots based on these data. As in the case of propane, first-order dependency is indicated. Comparison of the first-order lines in these figures with those in Figure 7 indicate a more gradual slope with the jet fuel, undoubtedly reflecting oxidative attack on the higher-molecular-weight hydrocarbons in the low-temperature regime.

Additional runs were made with Catalyst A at still higher equivalent space velocities, ranging as high as 150,000 hr.⁻¹. See conditions given in Table IV for Runs JT-5, JT-6A and JT-6B. This series of runs was made over the same charge of Code A catalyst. The higher space velocity in JT-6A was achieved by increasing the flow of diluent nitrogen, and the conditions in JT-6B were matched to those in JT-5 as a means of detecting any change in activity. The data obtained are summarized in Tables XVIII-A, XIX-A and XX-A, and plots based on these data are given in Figures 13, 10-A & 11-A. An inspection of these data and the first-order plots shows very little effect of space velocity on conversion, at a given temperature. The most probable explanation for this is the increase in system pressure, especially at the higher end of the range. Increased pressure would be expected to favor increased conversion if the diffusion of hydrocarbon into the pores and/or the adsorption of hydrocarbon onto the catalytic surface are rate-controlling steps. This is in line with the effect of using an excess of hydrocarbon, as brought out elsewhere [Section III-2-f-(1)].

The 150,000 hr.⁻¹ space velocity run was made at the upper limit of our test apparatus, and does not represent an upper limit for the catalyst. There was insufficient time to modify the apparatus to permit higher flow rates; therefore, the performance of the more active catalysts has not been fully evaluated.

(b) Effect of Sulfur

We were advised that Code A catalyst had been found insensitive to poisoning by the sulfur normally found in motor gasoline. Our analysis of the JP-7 fuel showed no sulfur present, down to the assay sensitivity limit (25 ppm). The JP-4 fuel samples contained 0.16% sulfur. The effect of this sulfur per se on catalyst performance was not isolated, but the results of the 60-hour test run and the activity checks before and after the run (Figures 18, 19 and 20) indicated little or no effect. Chemical analysis of the Code A catalyst used in these tests showed that the S content of the catalyst had increased from 0.03% to 0.47% at the end of the 60-hour performance test and that regeneration caused a reduction to 0.2%.

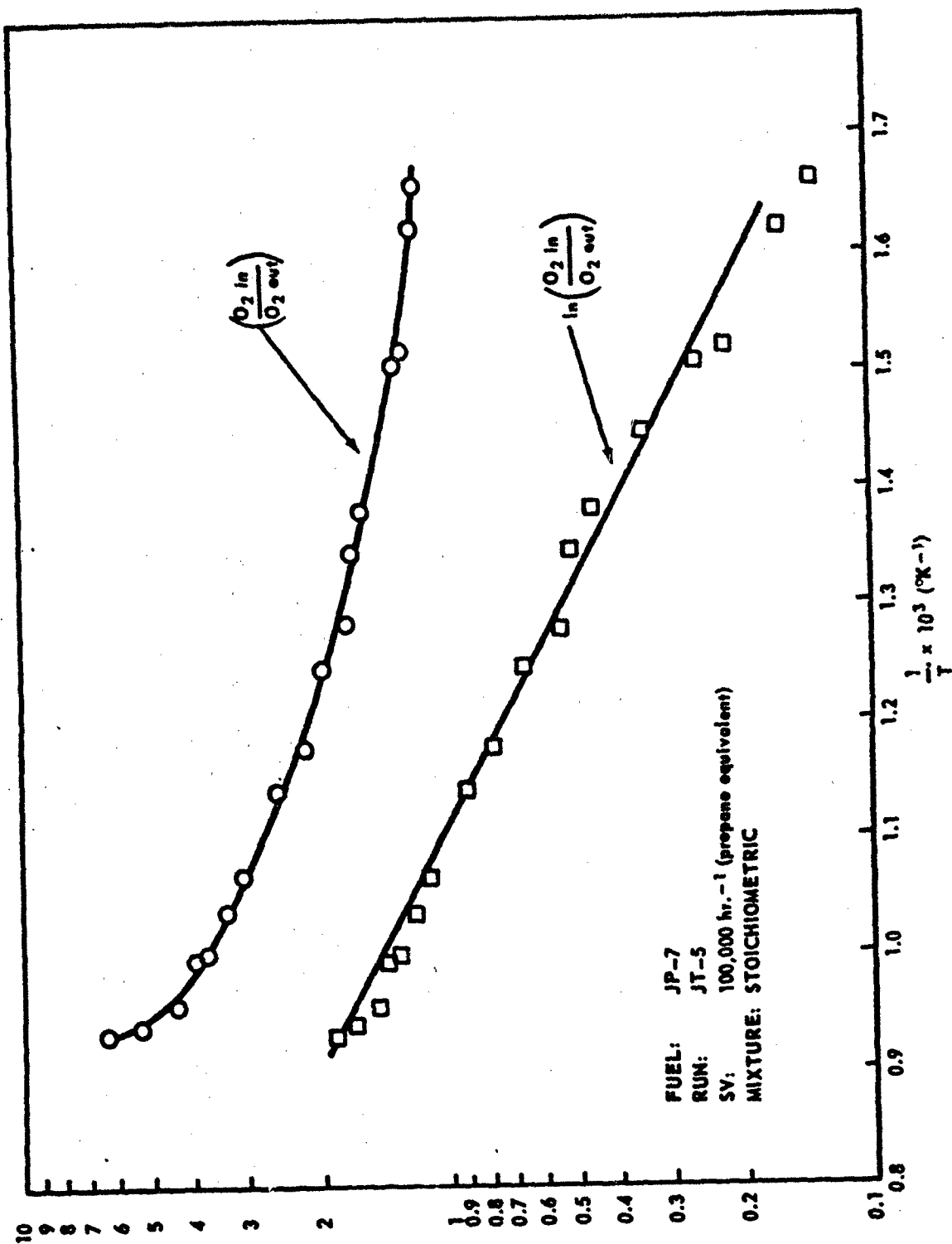


FIGURE 13. CODE A CATALYST - EFFECT OF TEMPERATURE ON OXYGEN CONVERSION

(c) Coke Deposition

It was not possible to calculate the production of coke in runs where liquid fuel was used, due to the inoperability of the hydrocarbon analyzer. However, there was direct evidence (Section III-2-f) of coke deposition with JP-4 and JP-7 fuels. The later discussion also describes a regeneration treatment which successfully removed deposits of coke. It appears from the available data that coking can be expected under excess fuel conditions, regardless of fuel type, but that no special difficulty would be presented unless a fuel were used that would allow metallic poisons to accumulate on the catalyst.

(d) Catalyst Type

Only one comparison was made between Code A and Code F catalyst using JP-7 fuel. The run conditions are given in Table IV (Runs JT-5 and JT-9), and data are given in Appendix Tables XVIII-A and X-A. Figure 7-A gives a plot of the data, and Figure 14 shows that catalyst A is clearly more active than Catalyst F, under these conditions.

(e) Conversion to CO₂

Data were obtained on conversion of JP-7 to carbon dioxide, as opposed to the monoxide, using the technique explained previously. A plot of fraction converted to CO₂ vs conversion level is shown in Figure 15, where it is seen that Code A and Code F catalysts behave similarly as in the oxidation of propane (see Figure 5). The fraction converted to CO₂ was calculated as equal to:

$$\frac{\% \text{ CO}_2 \text{ in exit gas}}{\% \text{ O}_2 \text{ in} - \% \text{ O}_2 \text{ out}} \times \frac{14}{9}$$

which is based on the chemical reaction:



Similar values obtained during the 60-hour run with JP-4 and Catalyst A are indicated in Figure 18, where it is seen that the fraction of oxygen converted to CO₂ is about 70%. This significantly lower value appears to be a function of fuel composition, possibly reflecting the higher aromatics content of the JP-4.

(3) Discussion

All of the above experimental findings indicate that JP-4 and JP-7 fuels offer no serious problems insofar as catalyst performance is concerned. The JP-4 tests are of special significance because the properties of the MIL-T-5161G samples used represent about the most deleterious that could be expected in field use, and because the tests were carried out over a period exceeding 60 hours. Several aspects remain to be explored in greater depth, particularly the performance effects associated with higher space velocities and a wider range of pressures.

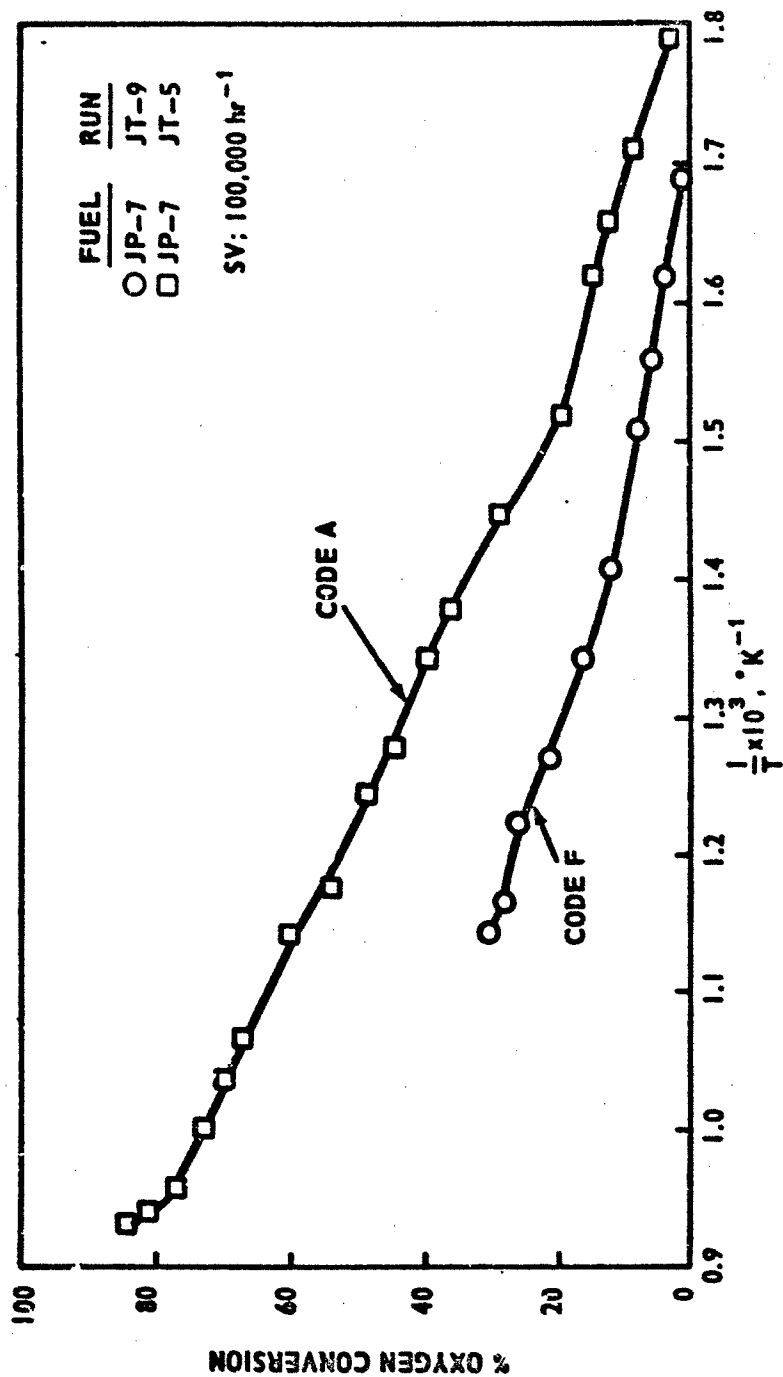


FIGURE 14. CATALYST PERFORMANCE COMPARISON WITH JP-7 FUEL

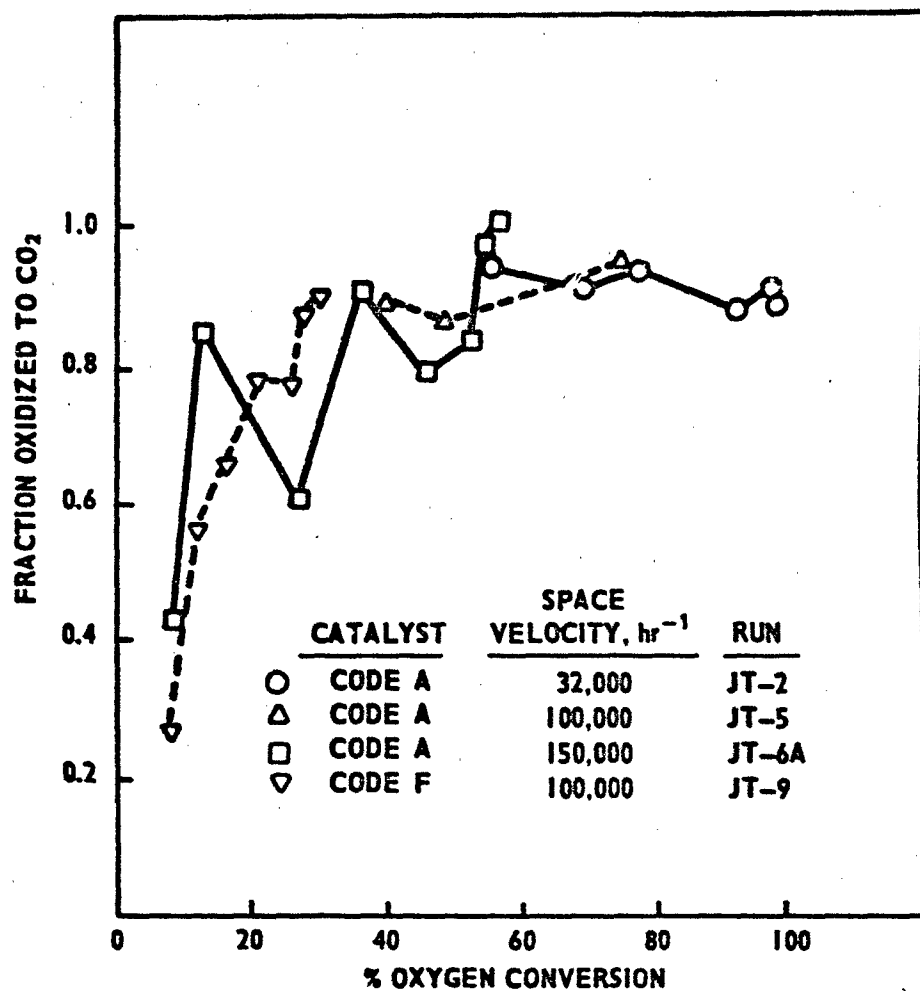


FIGURE 15. EFFECT OF CONVERSION LEVEL ON FRACTION OF REACTED JP-7 OXIDIZED TO CO_2

f. Optimization and Regeneration Studies

The experiments conducted in this part of the program were directed toward the selection of operating conditions that would most nearly represent satisfaction of the system performance targets. The various parameters studied are identified in the discussion which follows.

(1) Excess Fuel

Reactant ratio is one of the important operating parameters. If a fuel-lean mixture is employed, conversion of oxygen would be expected to decrease. If a fuel-rich mixture is employed, conversion of oxygen would benefit, but the rate of coke deposition might be excessive. A simplified picture of the process indicates that carbon contained in the fuel molecules may react to form one or more of the products: CO_2 , CO and C . The corresponding reactions consume different amounts of oxygen. Hence, when propane is used as fuel (thereby allowing use of the hydrocarbon analyzer) the oxygen, hydrocarbon and CO_2 content of the exit gas can be used to calculate the amount of coke formed, as carbon.

(a) Run CT-1 With Propane Fuel

An extended run was made to study the performance of Code A catalyst with propane fuel in varying degrees of excess. It was expected that the fuel-rich mixture would promote coke deposition, hence this was referred to as a coking run. The run, conducted over a period of 36 hours, was made up of three periods in which the excess of fuel was varied from 100% to 300%. (See Table VI, Run CT-1.) Computations made from the data are plotted in Figure 16.

The conversion of oxygen was above 95% throughout the run, attributable to both the excess of fuel and the maintenance of a "hot spot" temperature above 750°C . Examination of the propane conversion curve indicates coking during each of the periods. For example, during Period I the theoretical maximum oxidative conversion of propane is 50%; therefore, a substantial conversion to non-oxygen-containing products is inferred during the early part of the period. The shaded area below the coke curve represents the calculated amount of coke formed (as carbon) and implies a production of 60 grams during the entire test. More interesting is the shape of the coking curve in each period, showing an initial high rate of formation followed by a decline. This indicates the possibility of a change at the active catalytic surface (such as a change in oxidation state) representing an adjustment to the new hydrocarbon concentration.

Analysis of the catalyst used in Run CT-1 showed an accumulation of 4% (weight) carbon, representing only about 1 gram of the 60-gram calculated production.

(b) Run CT-2 With Propane Fuel

A second coking run of 60 hours duration was carried out using propane and Code A catalyst. Conditions are given in Table VI, and differed from those in Run CT-1 essentially as follows. The catalyst

TABLE VI. SUMMARY OF RUN CONDITIONS, COKING RUNS WITH PROPANE FUEL

Run No.	Catalyst: Code A										
	CT-1			CT-2							
	I	II	III	I	II	III	IV	V	VI		
Operating Period											
Reaction time, hr.	21	12	3	6.8	9.2	17.2	14.4	9.2	3.2		
Catalyst type	Code A			1 part Code A, 2 parts ceramic beads							
Catalyst volume, cc	25	25	25	75	75	75	75	75	75		
Flow Rates, cc./min.											
Nitrogen (g)	10,850	10,850	10,850	10,850	10,850	8,400	6,510	5,425	10,850		
Air (g)	2,380	2,380	2,380	2,380	2,380	2,380	2,380	2,380	2,380		
Propane (g)	200	300	400	100	200	200	200	200	100		
Space Velocity, ^m hr. ⁻¹	32,232	32,472	32,712	31,900	32,232	26,352	21,816	19,212	31,900		
Propane excess, %	100	200	300	0	100	100	100	100	0		
Nitrogen reduction, %	0	0	0	0	0	22.6	40	50	0		
Reactor inlet temp., °C.											
Min.	222	299	305	197	291	283	240	253	250		
Max.	306	307	307	331	341	343	332	259	346		
Ave.	264	303	306	264	316	313	286	256	298		
Furnace temp., °C.											
Min.	261	498	520	295	426	506	453	441	346		
Max.	525	520	520	513	522	524	481	451	540		
Ave.	393	509	520	404	474	515	467	446	440		
Hot spot temp., °C.											
Min.	780	751	761	720	721	761	754	800	756		
Max.	807	772	780		806	806	805	816			

*In Run CT-2 all space velocities are based on the volume of Code A (excluding diluent).

OPERATING CONDITIONS

PERIOD I: 100% EXCESS PROPANE
 PERIOD II: 200% EXCESS PROPANE
 PERIOD III: 300% EXCESS PROPANE

SPACE VELOCITY: 32,000-33,000 hr.⁻¹
 "HOT SPOT" TEMPERATURE: 751-807°C

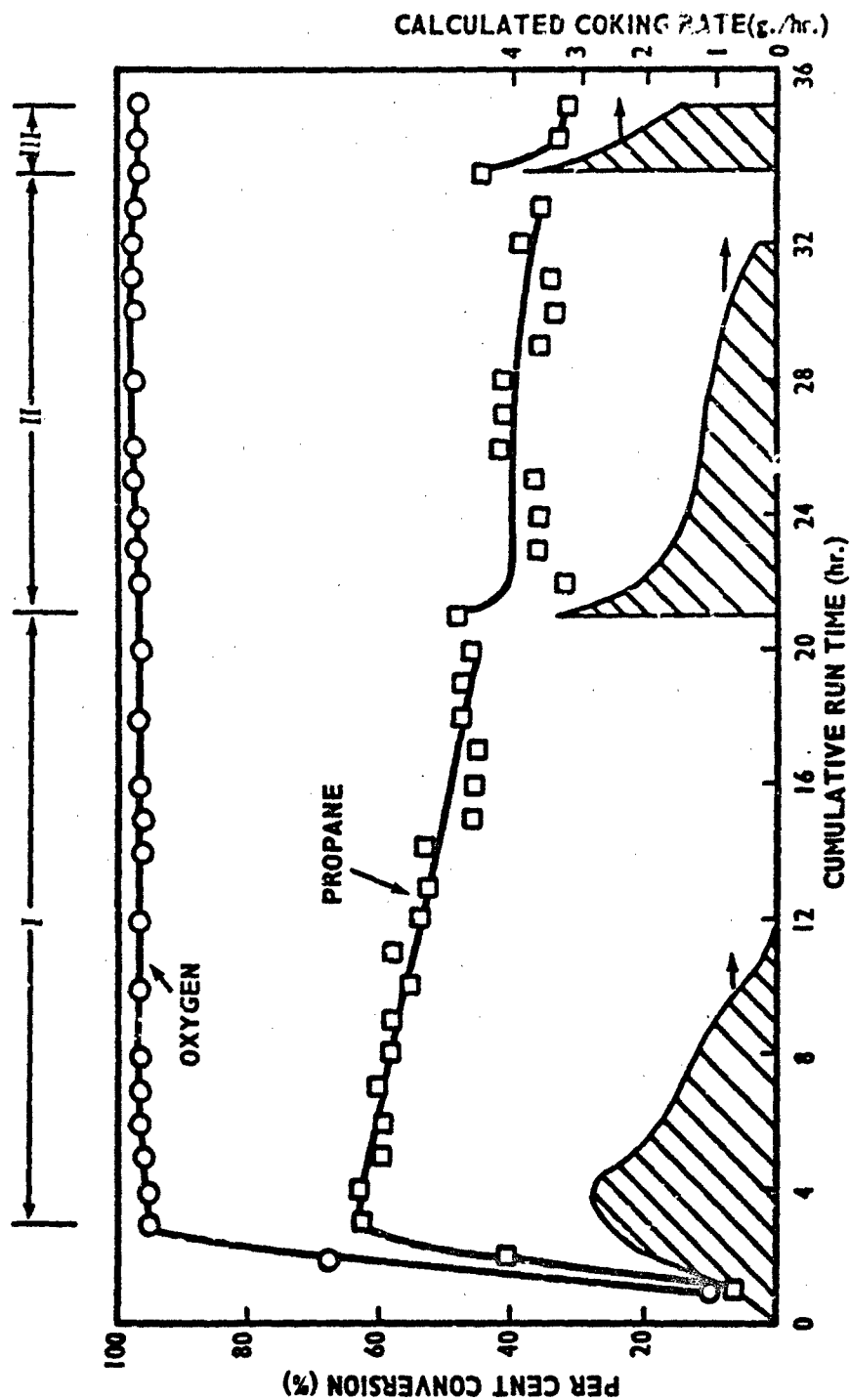


FIGURE 16. CODE A CATALYST PERFORMANCE DURING COKING RUN CT-1

was diluted with inert ceramic beads in the ratio of two parts beads to one part catalyst. During the six operating periods, variations were made in the amount of diluent nitrogen, and the amount of fuel was either stoichiometric or in 100% excess. Periods I and VI were made at "baseline" conditions, the latter representing a performance check. Except for these periods, the hot spot temperature was generally higher than in Run CT-1, despite the catalyst dilution, because of the reduced flow of nitrogen diluent.

Figure 17 shows the conversion of reactants to products during the run, including calculated production of coke as carbon. It can be observed in the Figure that conversion of oxygen rose to the 95+% level at the start of Period II, and remained there through Period V. The brief operation during Period VI produced results similar to those obtained in Period I. The calculated conversion of propane to coke was nil prior to Period V, except for a brief time during Period I. The high conversion to coke in Period V coincides with the highest catalyst temperatures recorded during the run, and suggests that catalyst bed temperature should be limited to 800°C. or even lower (under excess fuel conditions) in order to minimize coking. Looking at both coking runs together, the high coke production during Period I of Run CT-1 may in large part be attributable to localized overheating in the undiluted catalyst bed.

(c) Excess JP-7 Fuel

The effect of using excess fuel was studied further using JP-7 liquid fuel. Run JT-7 was made with a charge of catalyst that had been used previously in Runs JT-5, JT-6A and JT-6B. Conditions are given in Table IV, where it is seen that 100% excess fuel was employed, and the space velocity was 100,000 hr.⁻¹. A summary of the run data is given in Table XXI-A, and a plot of the conversion data appears in Figure 12-A. Comparison of the results with those of Runs JT-5 (Figure 13) and JT-6B (Figure 11-A) (same conditions except stoichiometric ratio) show that the excess fuel makes a significant difference in performance. The rate constant at 725°C. for Run JT-7 was found to be 373,000 hr.⁻¹, as compared to 143,000 hr.⁻¹ for Run JT-5. A deposition of coke took place in Run JT-7, as evidenced by the results obtained on regeneration of the catalyst (see Section III-2-f-(3) below).

(d) Excess JP-4 Fuel

A run of 60 hours duration was made to define the performance of Catalyst A while operating with an excess of JP-4 fuel typical of the MIL-T-5161G specifications. During most of the run, a mixture containing approximately 100% excess of JP-4 was used (see Table V) but, as shown in the table, there were periods during the first half of the run when the excess of fuel ranged from 45% to 400%. A summary of representative run data is presented in Table XXVI-A, and a plot showing the principal performance trends is given in Figure 18. Tables XXVII-A and XXVIII-A contain summaries of performance test results obtained with propane under standardized conditions before the 60-hour run, and Tables XXIX-A and XXX-A contain similar information obtained after the run. Plots of these data showing the usual kinetic relationships are given in Figures 19 and 20. Inspection of these figures gives little indication of a performance decline, within the limits of the scatter in the data. Figure 21 shows several of the temperature profiles obtained during the JP-4 run, as well as one taken immediately prior

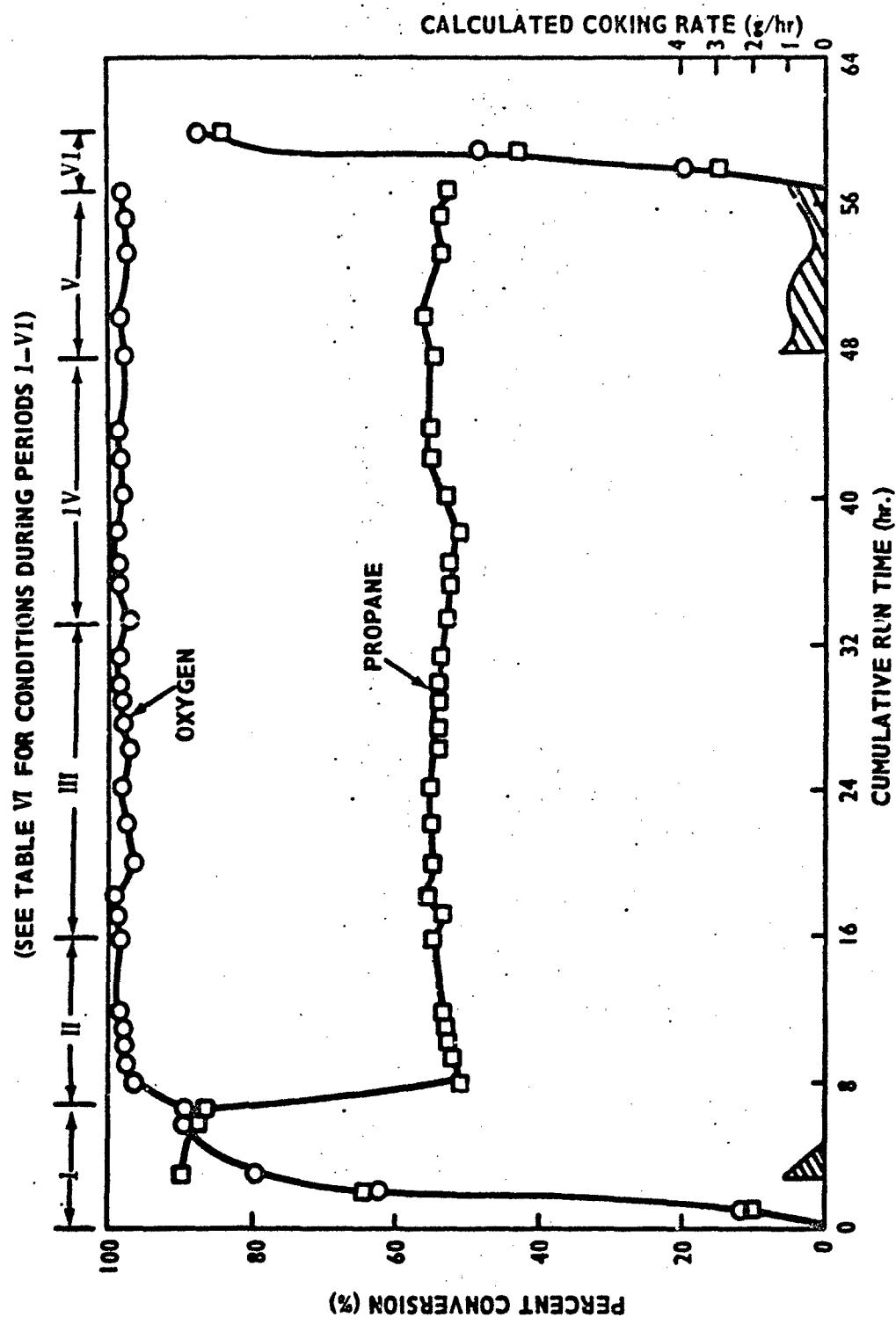


FIGURE 17. CODE A CATALYST PERFORMANCE DURING COKING RUN CT-2

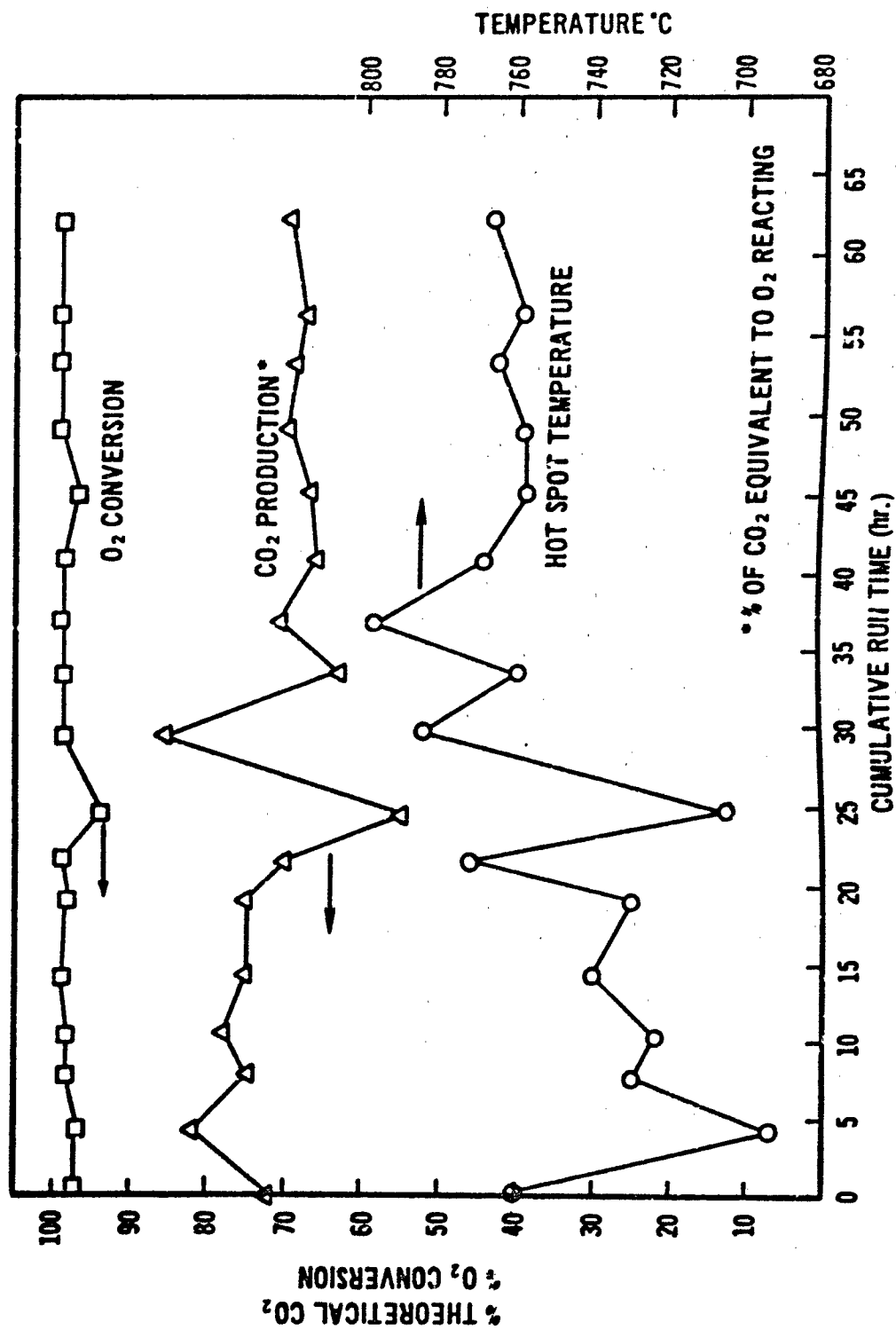


FIGURE 18. CODE A CATALYST PERFORMANCE DURING 60-HOUR TEST
WITH MIL-T-5161G FUEL

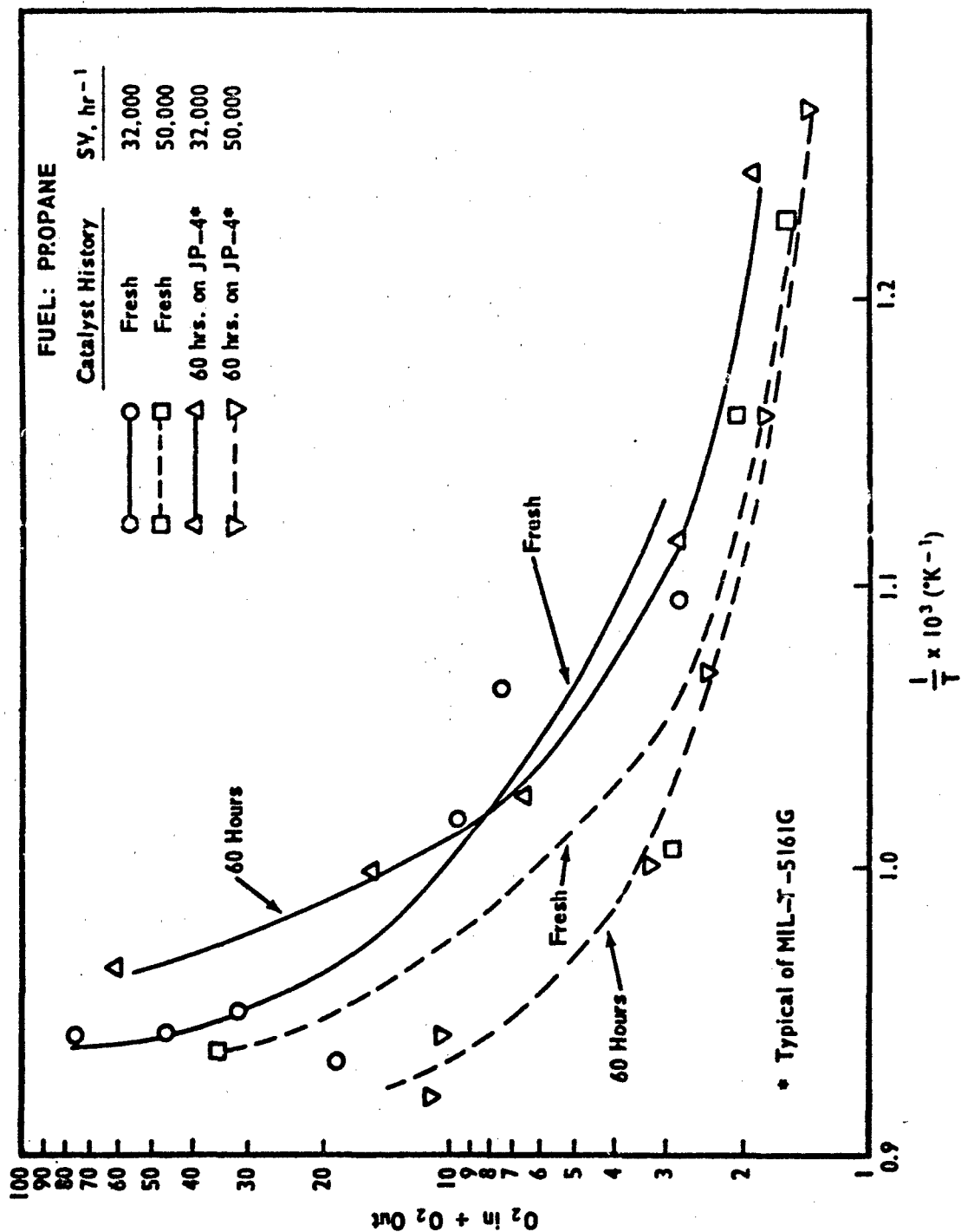


FIGURE 19. EFFECT OF 60-HOUR TEST WITH MIL-T-5161G FUEL ON ACTIVITY
ON CATALYST A (2nd ORDER PIOTS)

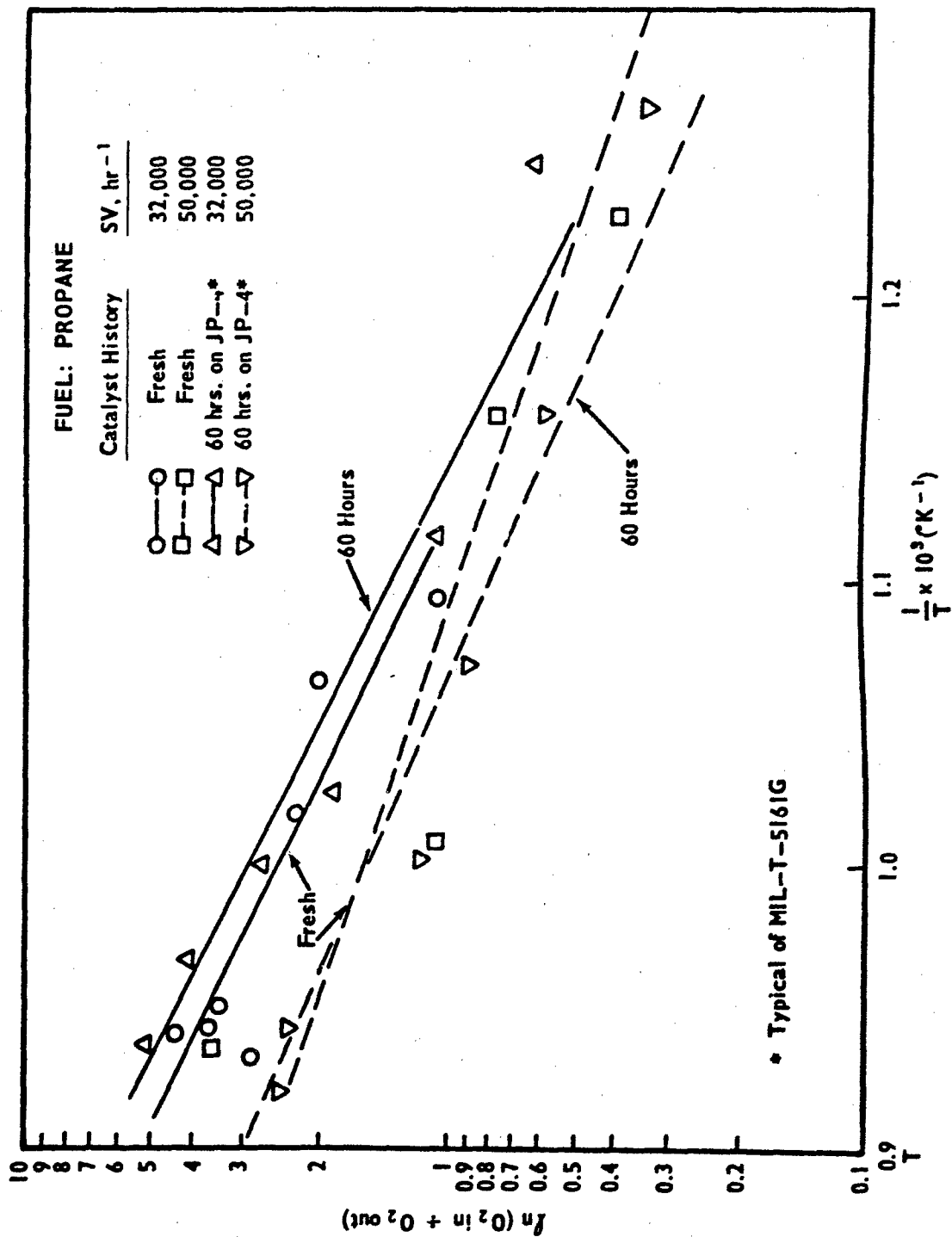


FIGURE 20. EFFECT OF 60-HOUR TEST WITH MIL-T-5161G FUEL ON ACTIVITY OF CATALYST A (1st ORDER PLOTS)

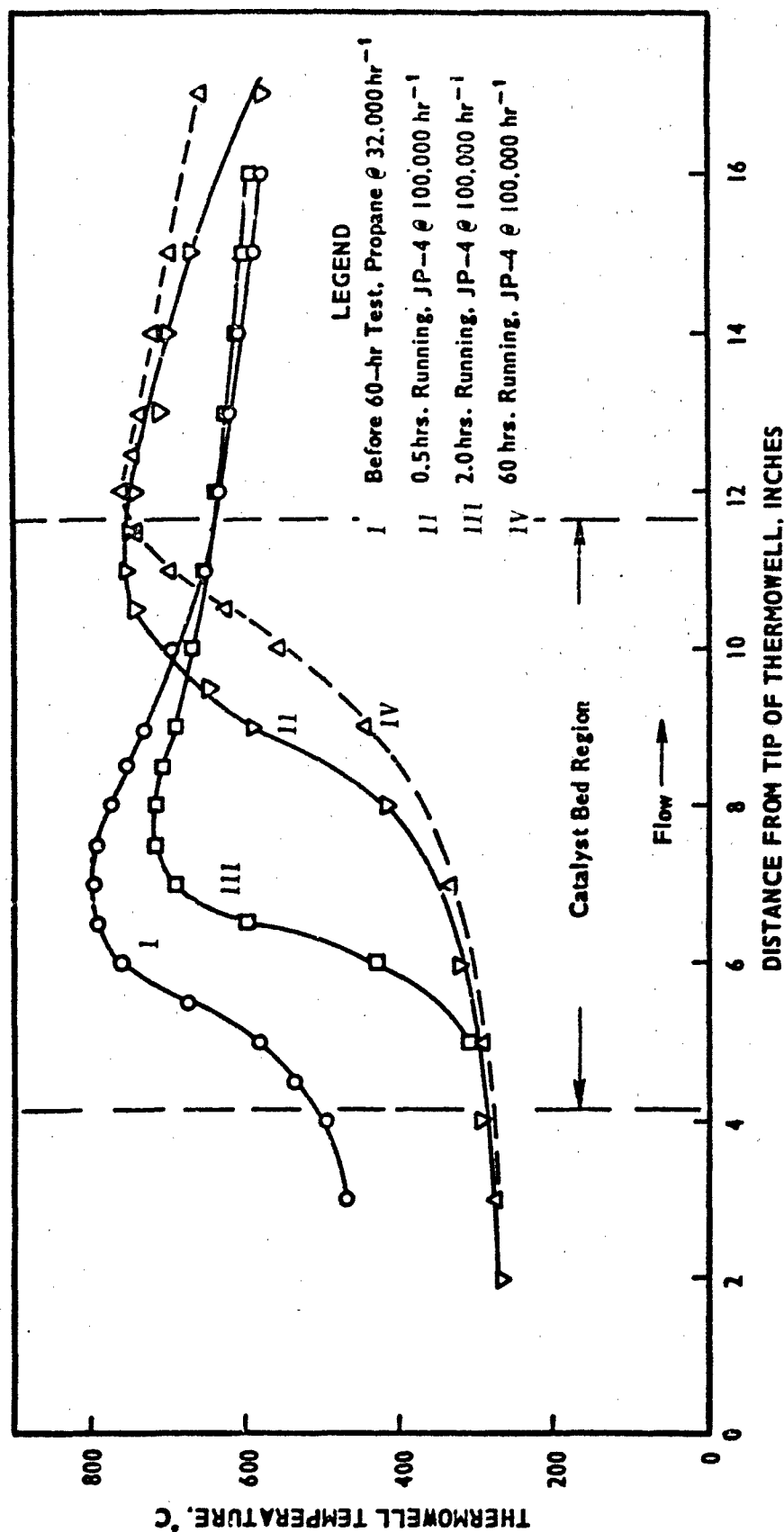


FIGURE 21. BED TEMPERATURE PROFILES DURING 60-HOUR TEST RUN
WITH MIL-T-5161G FUEL & CATALYST A

to the run while feeding propane fuel. As observed previously, the "hot spot" location is seen to shift position. Figure 18 shows that the fraction of oxygen converted to CO_2 may have declined about 10% over the course of the entire run, but was stabilized at the 70% level during the last 25 hours. The "hot spot" temperature in the central thermowell stabilized at about 765°C . over the last 25 hours.

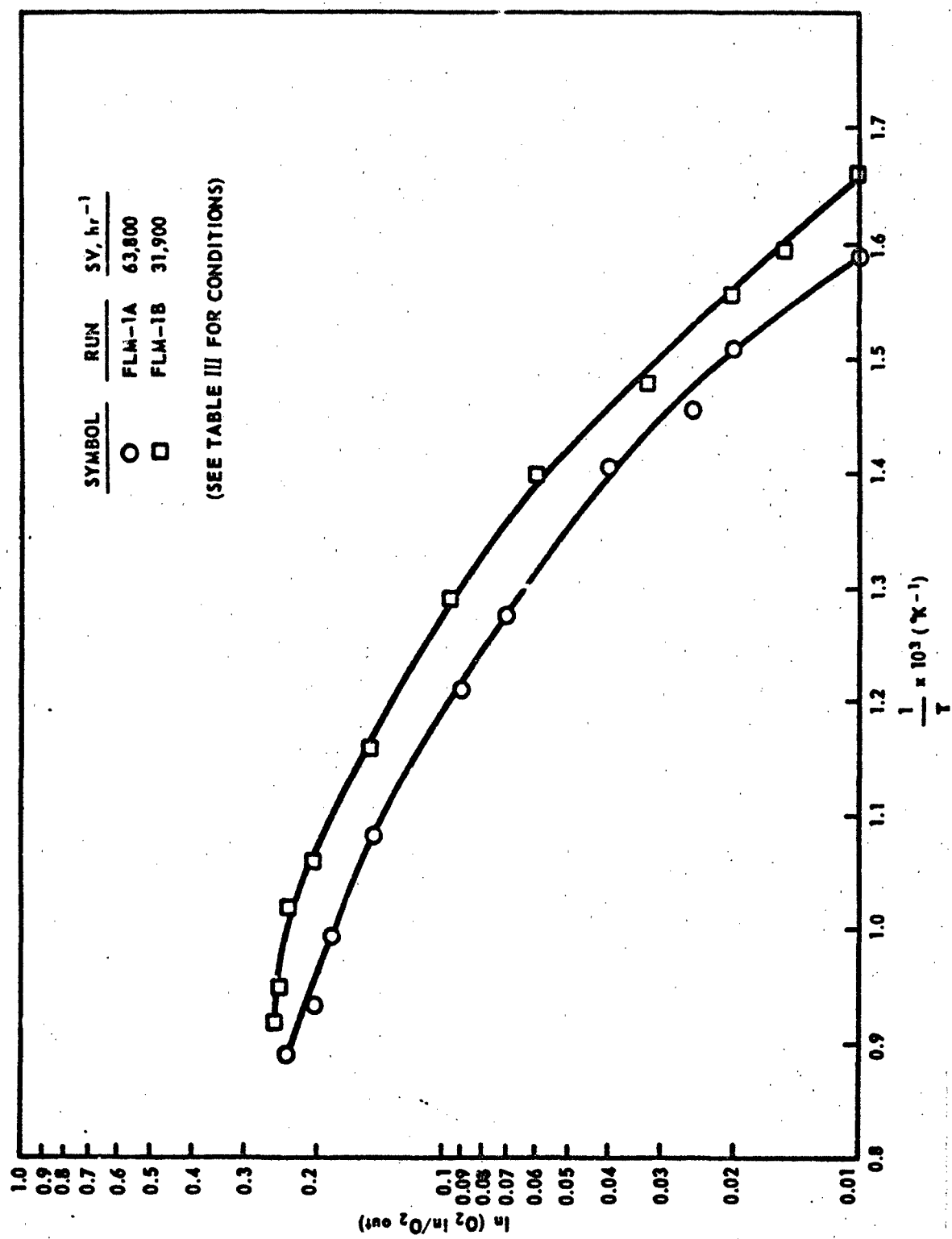
A sample of catalyst taken at the conclusion of the 60-hour JP-4 run contained 10.6% carbon, indicating a considerable deposition of coke. The specific surface of this sample was $139 \text{ m}^2/\text{g}$, as compared to $191 \text{ m}^2/\text{g}$ for fresh Catalyst A. It is not known if the level of coke had reached an equilibrium value, or if it was continuing to increase as the test progressed. The fact that the sulfur content of the catalyst was reduced from 0.47 to 0.20% during regeneration indicates that at least a large part of the sulfur was associated chemically with the coke deposit, rather than with the catalyst itself.

(2) Excess Oxygen

One possible arrangement in the inerting subsystem would utilize a two-stage catalytic reactor. As discussed elsewhere, this would have the advantage of limiting the amount of heat released within the catalyst bed, and would permit preheating of the fuel-air mixture (outside the normal combustibility limits) without danger of premature ignition. To test the performance of Catalyst A under conditions that would simulate this situation, Runs FIM-1A and FIM-1B were made using propane fuel. Run conditions are given in Table III, where it can be seen that no nitrogen diluent was employed, and that space velocities of $31,900$ and $63,800 \text{ hr}^{-1}$ were used. Summaries of the run data are given in Tables XXII-A and XXIII-A, and Figure 22 shows a plot of the first-order data obtained in each case. It is indicated by these results that the kinetics deviate considerably from the first-order relationship, and that conversions are below those obtained over the same catalyst under stoichiometric or fuel-rich conditions, again indicating the importance of hydrocarbon concentration in the rate-controlling step. Nevertheless, high conversion levels were attained (see tables), and it appears that the two-stage concept is feasible.

(3) Regeneration

The charge of catalyst contained in an operational catalytic reactor can most readily be regenerated without removing it from the reactor. Conceptually, either the reactor itself could be removed from the aircraft as a cartridge unit, or the regeneration could be performed in place (on the aircraft) by making connections to a service truck. In either event, the regeneration would involve passing a flow of oxygen-containing gases through the bed at a temperature sufficient to support combustion. The gas mixture should not be too rich in oxygen, otherwise the catalyst might become overheated.



To test this concept, a charge of catalyst used successively in runs JT-5, JT-6A, JT-6B and JT-7 (Table IV) was regenerated in place, i.e., the charge was held in the reactor tube while blanketed with nitrogen between the end of Run JT-7 and the start of regeneration. To perform the regeneration, the temperature of the furnace surrounding the reactor tube was raised while maintaining a flow of nitrogen. When the furnace temperature reached 476°C., the reactor inlet temperature was 270°C., and oxygen was introduced into the feed gas. The feed gas composition was 80% nitrogen and 20% air, corresponding to a reading of 4.28% on the oxygen analyzer. These conditions produced a moderate exotherm in the bed. The regeneration process was continued with close watch maintained on catalyst bed temperature and exit gas composition, using both the oxygen analyzer and samples for CO₂ determination by infrared analysis. Data are summarized in Table VII, which shows completion of the reaction after 85 minutes.

Following regeneration, the catalyst charge was used in two performance tests involving a fuel-lean mixture, presumably without any laydown of coke. Then it was given an activity check using propane at standard conditions (Run CCP-28, Table III). The results of this test are summarized in Table XXV-A, Appendix A. The change in activity is indicated in Figure 23, where conversion is compared against that of a charge of fresh catalyst under otherwise similar conditions (see data summary of Table XXIV-A and run conditions in Table III, No. CCP-26). In the 60-80% conversion range, the loss of activity is seen to be represented by a temperature change of 30-40°C. At the conclusion of Run CCP-28, a sample of the catalyst was found to have a surface area of 133 m²/g and to be free of carbon.

A second regeneration experiment was carried out using the charge of Code A catalyst that had received a propane activity check following the 60-hour run with JP-4 fuel. The regeneration conditions and data are summarized in Table VIII. The fact that the exotherm on regeneration was not as great as in the test mentioned above can be attributed to the catalyst dilution. It is seen in the table that the production of CO₂ was continuing when the regeneration operation was terminated. Chemical analysis also indicates that regeneration was incomplete; 2.4% carbon was found on the catalyst. Other changes caused by regeneration were a reduction in sulfur content from 0.47% to 0.20%, and an increase in pore volume (mercury porosimetry) from 0.49 to 0.60 ml/g. Specific surface was unchanged at 139 vs 135 m²/g.

The effect of this regeneration treatment on catalyst activity was checked using propane fuel, and a comparison is given in Figure 24. It can be seen that there was no substantial effect, and it cannot be said that there are any benefits to be gained by regeneration after 60 hours on stream with a 100% excess of JP-4 fuel.

Further work is needed over longer periods, to determine just how long the catalyst can be used without regeneration. It would be desirable to carry this work through at least two complete regeneration cycles, or 500 hours of reaction time, whichever comes first, and to operate at mixtures more representative of anticipated operations, i.e. approximately 10% excess fuel.

TABLE VII. REGENERATION DATA FOR CODE A CATALYST
AFTER TESTS WITH JP-7 FUEL

Elapsed Time (Min.)	Catalyst Bed Temp. (°C)	Reactor Inlet Temp. (°C)	Furnace Temp. (°C)	Exit Gas Analysis	
				Oxygen (% Vol.)	Carbon Dioxide (% Vol.)
0	542	270	476	4.28	0.00
10	674	270	480	0.20	4.43
15	749	270	484	0.20	---
20	757	270	488	0.27	3.53
27	763	270	495	0.45	3.40
29	763	271	496	0.55	3.40
35	736	271	505	0.88	2.75
42	732	271	507	1.42	2.26
50	697	272	509	2.38	1.53
57	650	271	509	3.20	1.13
63	620	271	505	3.80	0.36
75	568	271	503	4.22	0.00
85	556	271	500	4.28	0.00

TABLE VIII. REGENERATION DATA FOR CODE A CATALYST
AFTER TEST WITH MIL-T-5161G FUEL

Elapsed Time (Min.)	Catalyst Bed Temp. (°C)	Reactor Inlet Temp. (°C)	Furnace Temp. (°C)	Exit Gas Analysis	
				Oxygen (% Vol.)	Carbon Dioxide (% Vol.)
0	471	218	388	4.29	---
15	497	216	405	4.18	---
30	525	228	431	4.06	---
45	545	239	451	4.04	---
60	572	242	448	4.05	---
70	550	245	454	4.06	---
RESTART				3.84	---
80	590	273	498	3.72	0.132
95	595	273	499	3.76	0.066
110	607	278	510	3.76	0.04
125	607	278	512	3.82	0.04

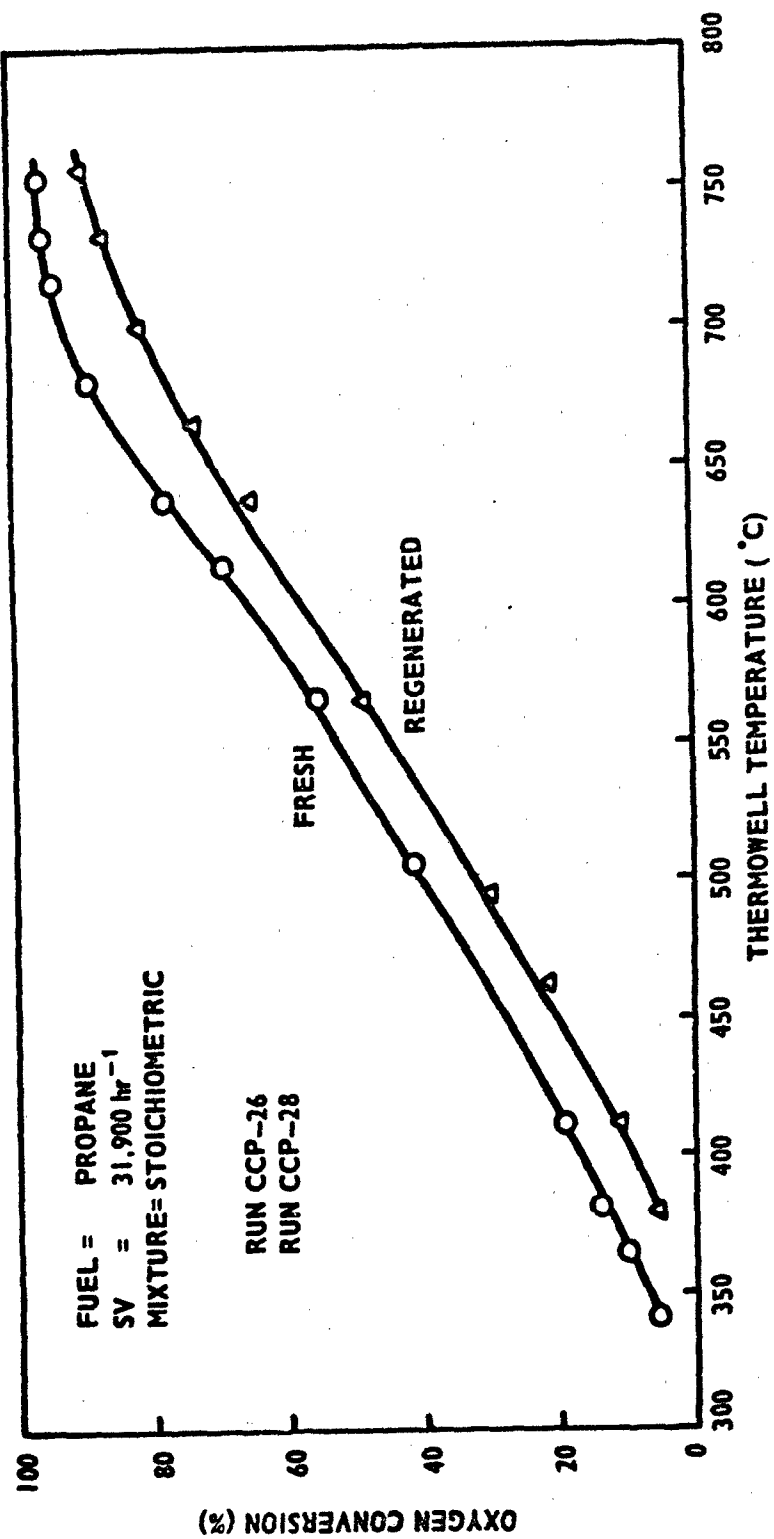


FIGURE 23. PERFORMANCE COMPARISON: REGENERATED vs FRESH CODE A CATALYST
 (REGENERATION FOLLOWED JP-7 FUEL RUNS)

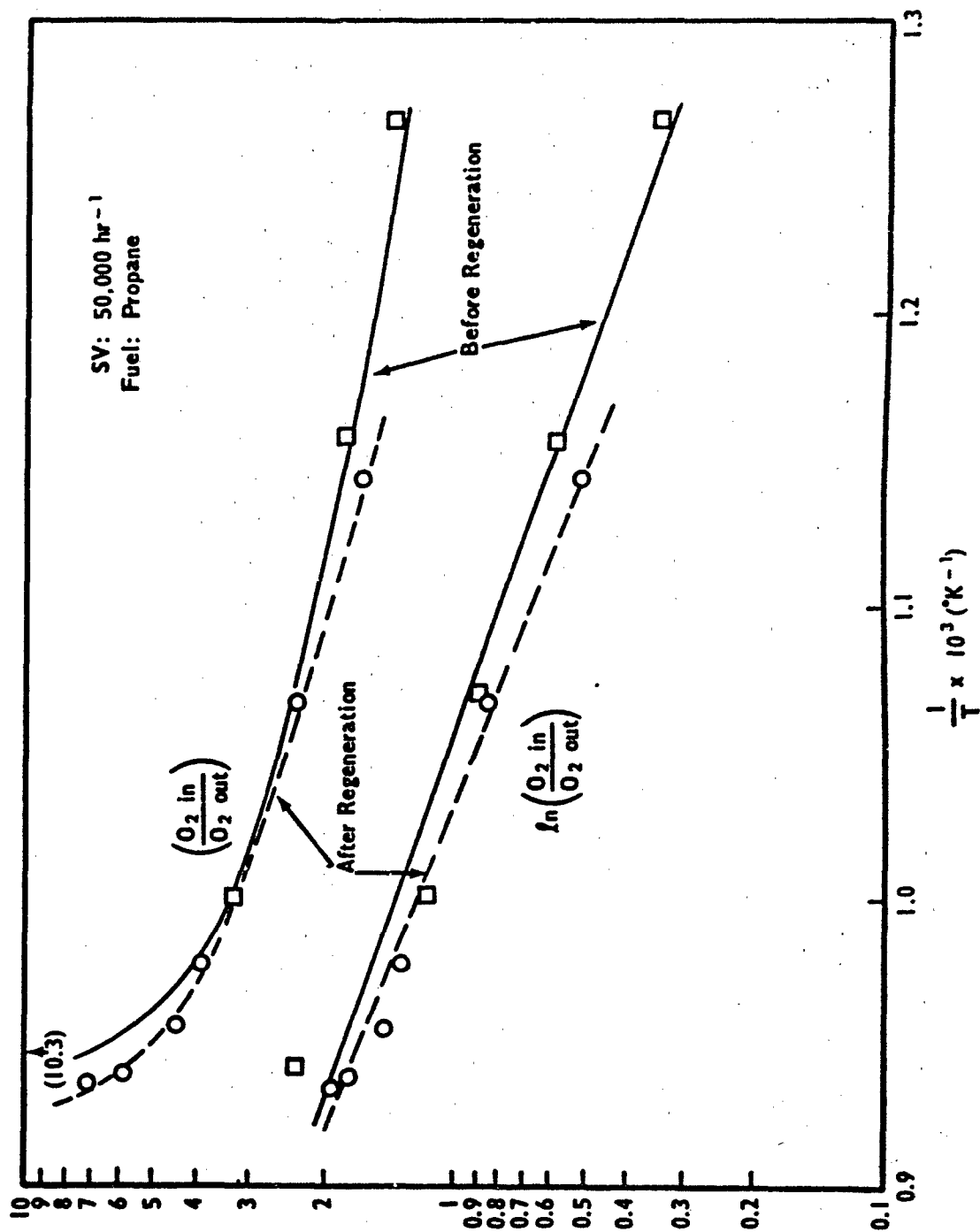


FIGURE 24. EFFECT OF REGENERATION ON PERFORMANCE OF CODE A CATALYST
AFTER 60-HOUR TEST RUN

(4) Activity Stability

Target performance calls for a minimum of 50 hours service before the catalyst requires regeneration, and 500 hours useful service with periodic regeneration. Several test runs with Code A catalyst provide data of pertinence.

Coking Run CT-1 (Table VI) was performed using propane fuel and a single charge of fresh catalyst. Total reaction time was 36 hours. No activity check under standard screening test conditions was made at the end of the run, but a surface area of $136 \text{ m}^2/\text{g}$ was measured. Coking Run CT-2 was also made using propane fuel, and was of 60 hours duration. Surface area determinations showed a drop from $191 \text{ m}^2/\text{g}$ to $164 \text{ m}^2/\text{g}$, somewhat less than in CT-1. Another sample of catalyst was used successively in Runs JT-5, JT-6A, JT-6B and JT-7 (Table IV); then in Runs FIM-1A, FIM-1B and CCP-28 (Table III). After this usage, surface area was found to be $133 \text{ m}^2/\text{g}$. The supplier of Catalyst A stated that results from tests in other programs had shown that deactivation due to loss of surface area is not severe until the area has decreased to about $50 \text{ m}^2/\text{g}$.

Periods I and VI during Run CT-2 allow a comparison of performance under standard screening conditions. Figure 25 shows plots of conversion vs temperature during these periods, and indicates a loss of activity equivalent to approximately 10% conversion at the same temperature level in the range of 60-90% conversion.

The smaller loss of specific surface in CT-2 as compared to CT-1 suggested that dilution of the catalyst was helpful in reducing the buildup of localized high temperature zones in the catalyst bed. The extended run with JP-4 fuel yielded a loss in specific surface equal to that found in CT-1, suggesting that there is also a fuel effect. Clearly, longer-term testing is indicated for a satisfactory definition of performance as a function of catalyst age and conditions of use. However, the performance results obtained using relatively low-quality JP-4 over a period of 60 hours are encouraging. Although there was a substantial accumulation of sulfur and carbon on the catalyst, this did not seem to affect its performance.

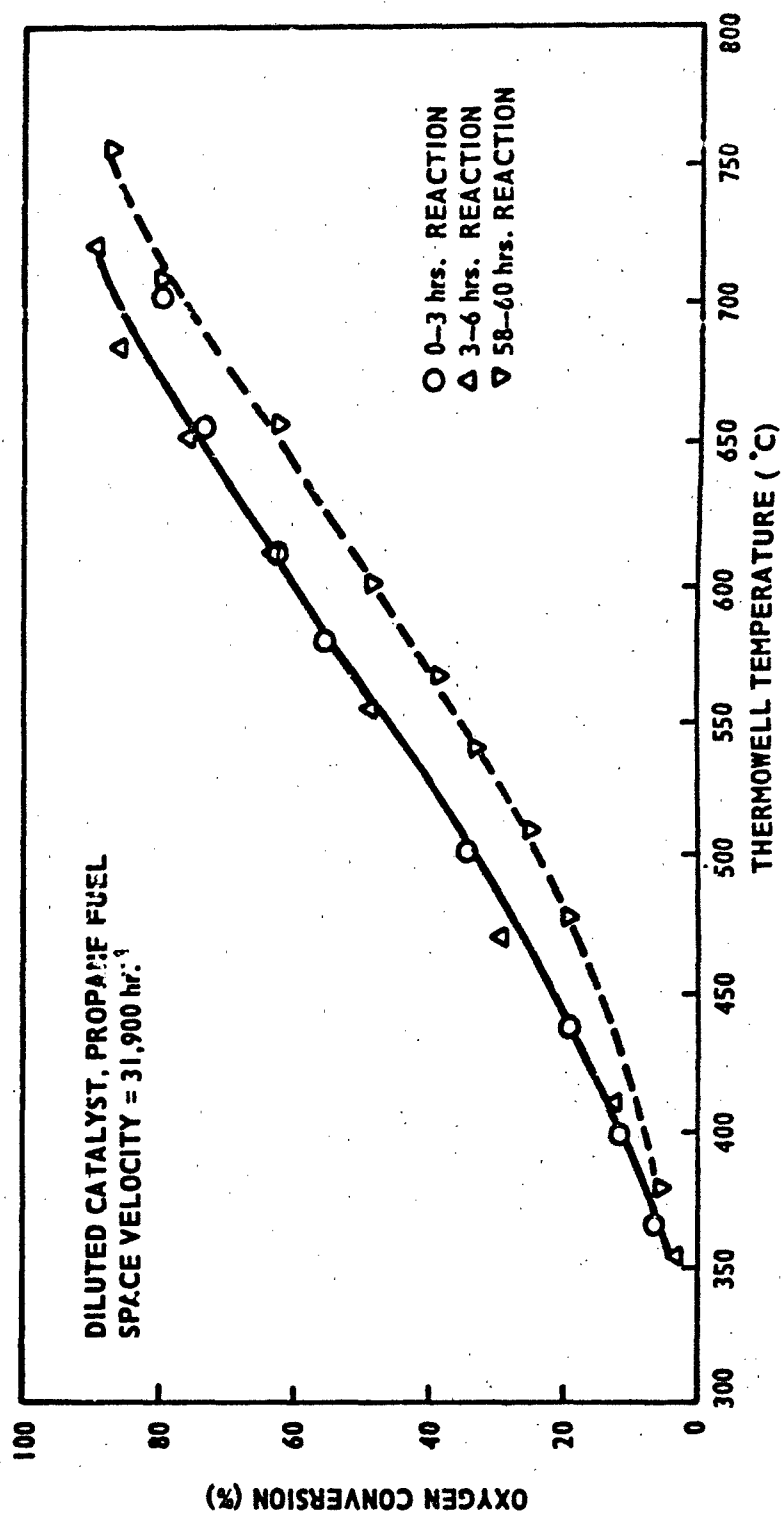


FIGURE 25. PERFORMANCE COMPARISON: FRESH vs AGED CODE A CATALYST

SECTION IV

WATER REMOVAL STUDIES

1. INTRODUCTION

The mechanisms by which drying agents function may be classified as follows:

- I. Chemical reaction
 - a. Formation of a new compound
 - b. Formation of a hydrate
- II. Physical absorption, constant relative humidity
(solid + water = saturated solution)
- III. Physical absorption, variable relative humidity
(a solution or liquid + water = diluted solution)
- IV. Adsorption on the surface of a solid

The effectiveness of any drying agent can be expressed in terms of two parameters, capacity and efficiency. Capacity refers to the amount of water that can be removed and held by a given weight of agent; it is generally expressed in weight-for-weight units. Efficiency refers to the degree of dryness that can be produced by the agent, and may be expressed in several ways, such as specification of the relative humidity, the water vapor pressure, or the dewpoint of the gas being dried.

In the present study, special attention is given to the performance of drying agents at elevated temperatures (between room temperature and the normal boiling point of water) because the operational unit will have to function in this range during flights at supersonic speed.

2. LITERATURE SURVEY

The number of materials which exhibit hygroscopic properties is large. Those listed and discussed briefly below are the ones most commonly used. A summation of the more important characteristics of each is given in Table IX.

TABLE IX. CHARACTERISTICS OF THE COMMONLY USED DRYING AGENTS

Drying Agent	Efficiency mg./liter gas. 25°C.	Capacity Lb. H ₂ O x 100/ Lb. Desiccant		Net Heat of Reaction, 25°C. ^a Kcal/mole H ₂ O	Advantages	Disadvantages
		25°C.	25°C.			
Barium Oxide (BaO)	2.8 ⁽¹³⁾	106	-5.7		1. Will dehydrate up to 1000°F. 2. Cheap 3. Efficient 4. Large capacity	1. Cannot be regen- erated. 2. Strong alkali 3. Reacts with CO ₂ to form scales which will not allow BaO to continue absorbing H ₂ O.
Boric Acid Anhydride (B ₂ O ₃)	150.0 ⁽¹⁴⁾	26	-3.5 ^b as HBO ₂		1. Does not react with CO ₂ 2. Efficient at 25°C. 3. Will dehydrate up to 175°C.	1. Efficiency decreases at high temp. (100°C) 2. Cannot easily be regenerated.
Calcium Chloride Anhydrous (CaCl ₂)	137.0 ⁽¹³⁾	97 ^c	-3.9		1. Cheap 2. Will dehydrate up to 200°C. 3. Absorbs rapidly	1. Danger of electro- lytic corrosion 2. CaCl ₂ ·6H ₂ O melts at 29°C.
Calcium Oxide (CaO)	656.0 ⁽¹³⁾	32	-19.5		1. High capacity	1. Corrosive 2. Hard to handle 3. Reacts with CO ₂
Calcium Sulfate (CaSO ₄)	67.0 ⁽¹³⁾	6.6 ^d	-6.5 ^d		1. Good drying efficiency 2. Not corrosive 3. Easily regenerated 4. Easily handled	1. Low capacity 2. Will not absorb above 100°C.

a. Excludes heat of condensation of water. Negative sign means heat evolved.

b. Value is -4.5 Kcal/mole if hydrate is H₃BO₃.

c. Additional water is absorbed in liquid phase.

d. Corresponds to hemihydrate, CaSO₄·½ H₂O.

(continued)

TABLE IX (continued)

Drying Agent	Efficiency mg./liter gas, 25°C.	Capacity lb. H ₂ O x 100/ lb. Desiccant 25°C.	Net Heat of Reaction, 25°C. ^a Kcal./mole H ₂ O	Advantages	Disadvantages
Lithium Chloride (LiCl)	----	45	-4.3	1. Non-toxic 2. Concentrated solutions not readily solidified 3. Less corrosive than CaCl ₂ 4. Best of the halides 5. Scale formation is usually no problem.	1. Will not absorb H ₂ O above 98°C.
Phosphorus Pentoxide (P ₂ O ₅)	3.6 (13)	38	-15.8	1. High drying efficiency 2. Good capacity	1. Difficult to handle 2. Corrosive 3. Becomes wet and sticky when saturated. 4. Strongly acid 5. Should never be heated above 130°C.
Silica Gel	70.0 (13)	40	-0.4	1. Good drying efficiency 2. Not corrosive 3. Easily regenerated 4. Easily handled	1. Drying performance poor at pressures below 1 atm. and temperatures above 100°F.
Anhydrous Magnesium Perchlorate (Mg(ClO ₄) ₂ ·0.1H ₂ O)	0.2 (13)	48	-5.5	1. High drying efficiency 2. Large capacity 3. Chemically neutral	1. Not suitable for flammable or acid gases (reacts to form explosive perchloric acid)
Potassium hydroxide (KOH)	939 (13)	64	11.4	1. Inexpensive 2. High capacity	1. Corrosive 2. Disintegrates in water obstructing gas flow.

Barium Oxide

Barium oxide is used primarily as a laboratory drying agent. It is one of the most active dehydration agents, and is the only agent which continues its drying action even at a red heat. It absorbs rapidly, with the evolution of considerable heat, forming barium hydroxide which is stable at least up to 1000°C. Further addition of water gives a series of hydrates, $\text{Ba(OH)}_2 \cdot \text{H}_2\text{O}$, $\text{Ba(OH)}_2 \cdot 3\text{H}_2\text{O}$, $\text{Ba(OH)}_2 \cdot 8\text{H}_2\text{O}$, $\text{Ba(OH)}_2 \cdot 16\text{H}_2\text{O}$.

Barium hydroxide reacts with carbon dioxide to form barium carbonate, which is a poor, insoluble desiccant. This carbonate forms scale on the surface of the BaO , interfering with its drying properties.

Boric Acid Anhydride (boric oxide)

There is little in the literature on boric oxide performance. In tests run at 23°C., it performed efficiently until moisture to the extent of about 28% of its weight had been absorbed⁽¹⁵⁾. The change from the anhydride to metaboric acid requires 25.8% of water. Boric oxide is more efficient than sulfuric acid and calcium chloride but is somewhat inferior in this respect to phosphorus pentoxide and magnesium perchlorate. No reference to a reaction of boric oxide with carbon dioxide was found.

Calcium Chloride

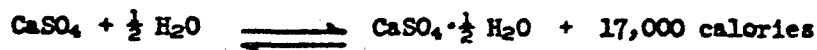
The outstanding advantage of this agent is its low cost. When used in a desiccator, anhydrous CaCl_2 is rapid in its action (7.5 - 15 min. to reach equilibrium), but its efficiency is inferior when compared to the three most efficient drying agents, namely, phosphorus pentoxide (P_2O_5), barium oxide (BaO), and magnesium perchlorate ($\text{Mg(ClO}_4)_2$).

Calcium Oxide

As a dehydrant, it is primarily used to remove small amounts of water from organic liquids. The reaction rate of CaO with H_2O increases rapidly as the temperature approaches 100°C. However, calcium hydroxide reacts with carbon dioxide, and air-slaked (carbonated) CaO is not a good desiccant.

Calcium Sulfate

Calcium sulfate is used as a desiccant of high efficiency and unusual versatility. Under the trade name of Drierite it is widely used in the laboratory and in industry for drying solids, organic liquids, and gases. At low temperatures, the dihydrate of CaSO_4 is stable, but at temperatures of interest in this program the reaction involved in the absorption of water vapor is as follows:



and represents the absorption of 6.6% by weight of the anhydrous salt. Since the reaction is reversible indefinitely, the drying agent may be used and regenerated through many cycles of operation. The drying efficiency, determined by the equilibrium vapor pressure of the system $\text{CaSO}_4\text{-CaSO}_4\cdot 0.5\text{H}_2\text{O}$, is approximately 0.005 mm Hg at 25-30.5°C., corresponding to a residual moisture content of 0.067 mg of water vapor/liter, or 4 ppm.

Although Drierite has served at temperatures between 100°F. and 200°F., it is commonly used at temperatures of 100°F. and below.

Lithium Chloride

Lithium chloride is the most efficient of the halides for the removal of water vapor. The three hydrates are $\text{LiCl}\cdot\text{H}_2\text{O}$, $\text{LiCl}\cdot 2\text{H}_2\text{O}$, and $\text{LiCl}\cdot 3\text{H}_2\text{O}$.

Lithium chloride has other favorable properties besides its ability to produce a low relative humidity. The solutions are more stable to air and less corrosive than the other halides. The carbonate salt is a thousand times more soluble than calcium carbonate, CaCO_3 , and about a hundred times more soluble than MgCO_3 . Therefore, scale formation is usually no problem.

Phosphorus Pentoxide (P_2O_5) and Phosphoric Acids

Phosphorus pentoxide is so efficient it is used as the reference point for evaluating other drying agents. The properties of P_2O_5 are affected by the method of preparation. Its normal vapor pressure is 760 mm Hg at 250°C. At higher temperatures, the crystals polymerize, the vapor pressure falls to a few mm of Hg, and other properties are affected. Because of its high vapor pressure, P_2O_5 should never be heated above 130°C. Its main advantages are a high absorption rate and the ability to produce very low vapor pressures of water.

Silica Gel and Other Solid Adsorbents

The silica gels are the most widely used of the agents in Class IV. They are classed as amorphous solid adsorbents. Crystalline adsorbents such as certain zeolite compounds also belong in Class IV, and are characterized as having higher capacity in the low water concentration ranges and a less pronounced loss of performance with increasing temperature, as compared to the amorphous type.

Perchlorates

Magnesium perchlorate is among the most efficient drying agents. Anhydrous magnesium perchlorate has very strong desiccant properties even at 135°C.; its various hydrates show good capacity, and even the highest hydrate ($6\text{ H}_2\text{O}$), is an efficient drying agent. There is one very important drawback, however. The perchlorate should never be used in the presence of organic compounds or acids since perchloric acid is violently explosive.

Sodium and Potassium Hydroxide

Alkali hydroxides are used primarily when it is necessary to remove both moisture and traces of acid gases, such as carbon dioxide and hydrogen sulfide. Regeneration is not practical with the alkali hydroxides.

3. SELECTION OF FEASIBLE METHODS

In order to reduce the water content of the ballast gas to the lowest possible level (target = 5 ppm), a dual system appears most practical. The gases will first be passed through a drying agent of high capacity and reasonable efficiency, then contacted with a high-efficiency drying agent to assure the dryness required. The advantages of this arrangement are that some high-capacity agents can absorb several times as much water as the common high-efficiency agents, and the high-capacity agents characteristically have a weaker chemical affinity for the absorbed water, hence liberate less heat per pound of water absorbed. Because of anticipated coolant limitations, a reduction in heat load helps to reduce the overall weight of the inerting package, and/or improve its efficiency.

Agents in Classes II and III (see above) involve liquids or the formation of liquids, and are not considered in this study because of difficulties anticipated with shifting attitudes and entrainment.

It is clear from consideration of the essential difference between equilibrium absorption and that which is attainable in a flow system that conditions favoring rapid pickup of moisture are desirable. For a given agent, this means utilization of the smallest practical grain size in order to increase the "effectiveness factor", i.e. minimize the limitation in overall rate caused by pore diffusion.

Agents that decompose water can be considered for final cleanup (a possible third stage), as long as the resultant volatile products are non-hazardous and non-injurious to the fuel handling subsystem and the jet engines. Metal hydrides, for example, would be objectionable due to the liberation of hydrogen, the presence of which would greatly widen the limits of flammability of the vapors in the fuel tanks. Calcium carbide, however, may be suitable. The acetylene generated in its reaction with water would be soluble in the jet fuel, and would have little or no effect on the flammability limits. In the event calcium carbide is considered further, the presence of small quantities of acetylene in the fuel delivered to the engines would have to be verified as non-objectionable.

4. PERFORMANCE TESTS

a. Selection of Candidate Agents

The following qualifications are highly desirable for agents used in the removal of water under the anticipated conditions.

- High degree of reactivity
- Large capacity
- Little change in efficiency with rise in temperature, up to 100°C.
- No tendency to react with CO₂ or hydrocarbons
- Ability to function at low pressures
- Low heat of reaction.

Consideration of the information in the literature relating to various candidates led to these findings:

- Perchlorates are not suitable because hydrocarbons or acid gases react to form explosive perchloric acid.
- Silica gel and other adsorbents cannot be considered unless means are devised for maintaining the drying agent at temperatures where performance is satisfactory.
- Oxides which react with CO_2 to form insoluble carbonates cannot be used. The carbonates are poor desiccants and they form barriers (scales) on the surface of the oxides, destroying the desiccant function. This prevents consideration of BaO and CaO .
- Calcium sulfate, lithium chloride, and phosphorus pentoxide cannot be used above 100° , 98° and 130°C. , respectively. The volatility of P_2O_5 merits special attention.
- For desiccants not excluded or limited by the above considerations, little or no information is available concerning capacity, efficiency and rate of absorption at temperatures in the range of interest.

A limited number of agents were selected for experimental testing, and they are listed below together with grade designations.

- Calcium chloride, anhydrous, reagent A.C.S. grade
- Calcium sulfate, anhydrous, "Drierite"
- Lithium chloride, reagent grade
- Potassium hydroxide, reagent A.C.S. grade
- Boric anhydride, analytical reagent grade

b. Procedures

(1) Analysis

Three of the desiccants were analyzed before use. Determination of water was done by the Karl Fisher method. This method was unsatisfactory for boric anhydride because of an interference. The data obtained were as follows:

calcium chloride	0.71%
calcium sulfate	0.061%
lithium chloride	0.72%

(2) Performance Test Apparatus

The candidate agents were evaluated experimentally using an assembly of apparatus shown in Figure 26. This setup made it possible to feed mixtures of humidified nitrogen and carbon dioxide to an absorption train consisting of three U-tubes in series. The gas mixture was capable of simulating the expected real situation in two essential respects:

- Regulated flows of preheated dry nitrogen and carbon dioxide represented the products of complete combustion of a hydrocarbon, ex water.
- A thermostated humidifier was used to humidify the dry gas mixture to a desired level.

It is seen that the 3 U-tubes were connected in series within a thermostated, stirred bath. The bath insured a uniform, known initial temperature, and provided an isothermal environment for each U-tube under test. Not shown in the figure is an auxiliary tank and piping system that made it possible to raise and lower the bath medium to facilitate the installation and removal of the tubes. The gas mixture leaving the third U-tube was directed through an air coil (necessary in elevated temperature runs) to the indicating-recording hygrometer, a Beckman Model 719 instrument with range of 0 to 1,000 ppm water. Additional data were read by means of an indicating potentiometer, to obtain the temperature of the agent within each of the U-tubes.

(3) Test Procedure

Using a drybox at the critical steps, clean U-tubes were tared and filled with the test agent, then reweighed and assembled into the apparatus as indicated in Figure 26. A volume of 40 cc. of agent was charged to each tube. The bath level was raised to completely cover the U-tubes, and leak tests were conducted. When the U-tubes were in thermal equilibrium at the desired bath temperature, the flow of gases was begun.

In all of the runs, a standard mixture comprising 51% CO₂ and 49% nitrogen was fed to the test apparatus at a combined flow rate of 2.94 liters/minute. Passage through the packed ceramic beads contained in the preheater served to insure good mixing as well as to preheat the gases (37°C. preheater exit temperature). Sparging of the gases into water maintained at constant temperature in the humidifier resulted in a controlled humidification. At a humidifier liquid temperature of 34°C., the gases entering the absorption train were found to contain 49,000 ppm water, or 0.04 grams water per liter of dry gas, and this was the standard level of humidification.

For runs made at the relatively low bath temperature of 40°C., water was used as the bath medium, but for the higher-temperature runs glycerine was used.

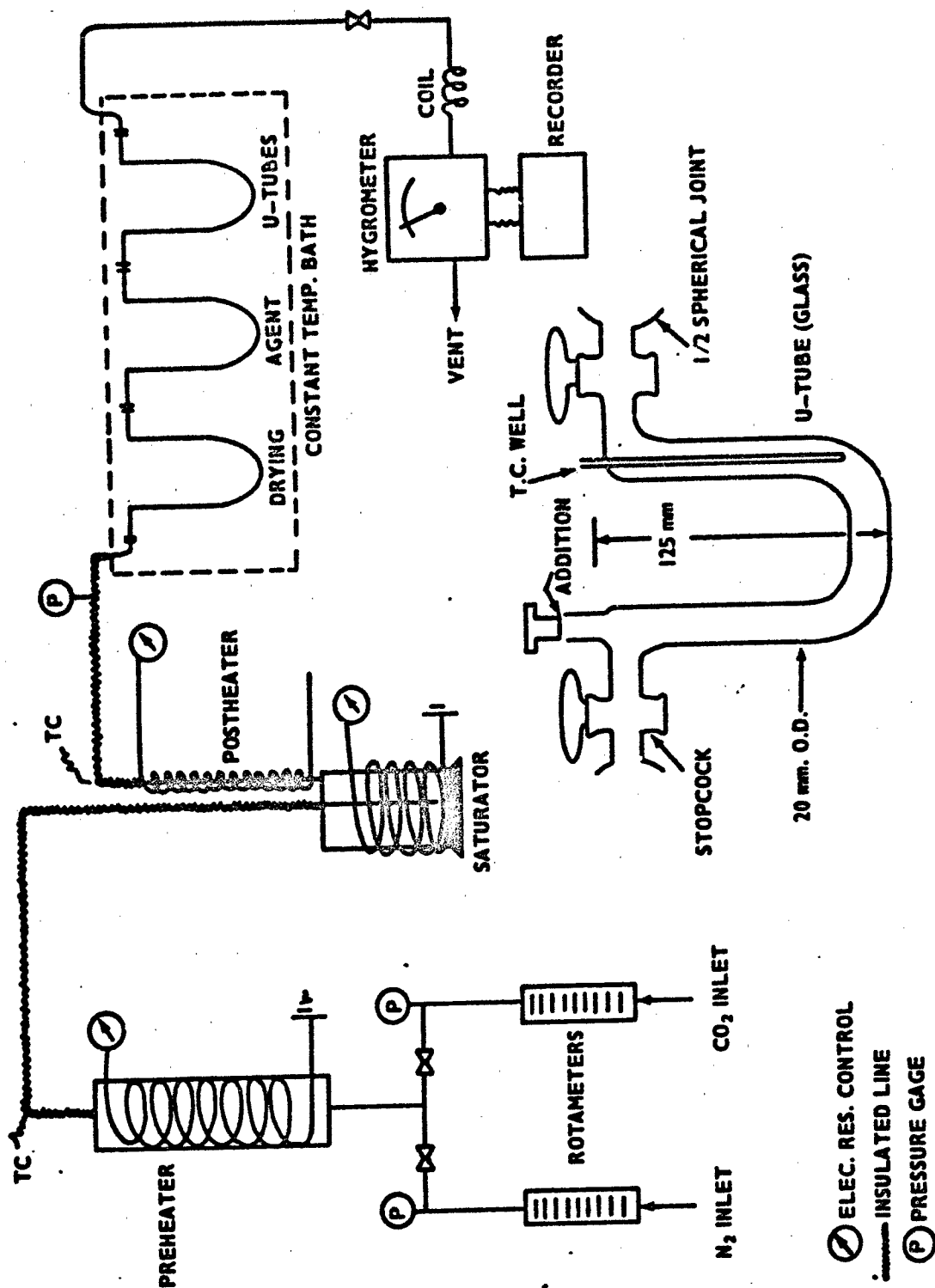


FIGURE 26 EXPERIMENTAL DRYING AGENT TEST APPARATUS

During each run the flow of gases was turned off periodically, the stopcocks on the U-tubes closed, and the tubes removed and weighed on a four-place Mettler balance. Care was taken before weighing to remove all traces of bath liquid from the exterior surfaces of the tubes. All increases in weight were attributed to absorption of water. As an additional precaution to guard against error, a glass wool plug was inserted on the exit side of each U-tube to keep the drying agent from being removed by entrainment in the gas stream.

The temperature of the agent in each U-tube was monitored during a run to obtain an indication of where absorption was taking place.

The static pressure of the gases entering the absorption train was kept constant by venting some of the exit gases. During most of the runs, a pressure of 5 psig was maintained. In some runs it was necessary to insert an air coil in the line leading to the hygrometer in order to cool the gases to the recommended measurement temperature.

c. Results

The five drying agents listed previously were tested in the apparatus described above, and the results obtained were as follows.

(1) Calcium Sulfate (CaSO_4)

One set of experiments was conducted using a U-tube bath temperature of 40°C . Figure 27 shows how the absorption in each of the U-tubes varied with total flow of gas. Note also that the exit water content (efficiency of complete train) is indicated in the figure. The amount of absorption in successive tubes decreased as the gases became drier in the process of moving through the absorption train. After passage of 400 liters of gas, the water uptake in the first tube approached 12.5%, somewhat above the capacity reported in Table IX. Figures 28, 29 and 30 each show a line representing the absorption of water by calcium sulfate at 40°C . The data for Figure 28 are for the first tube only, hence represent a space velocity (SV)² of $5,700 \text{ hr.}^{-1}$. Figure 29 covers the first 2 tubes, equivalent to $2,900 \text{ hr.}^{-1}$ SV, and Figure 30 represents 3 tubes and $1,900 \text{ hr.}^{-1}$ SV. One aspect from which the data can be viewed is the relationship between capacity and efficiency. As stated previously, CaSO_4 has high efficiency up to an absorption of 6.6% corresponding to formation of the hemihydrate, $\text{CaSO}_4 \cdot \frac{1}{2} \text{H}_2\text{O}$. Therefore, about half of the water held in Tube No. 1, Figure 27 is held loosely as capillary water. Figure 27 also shows a large rise in exit water level occurring somewhere between 300 and 360 liters. Reference to Figure 30 indicates this corresponds to an absorption of 7% in the complete train, very close to the hemihydrate point.

²gas flow rate (liters/hour) \div bulk volume of agent (liters).

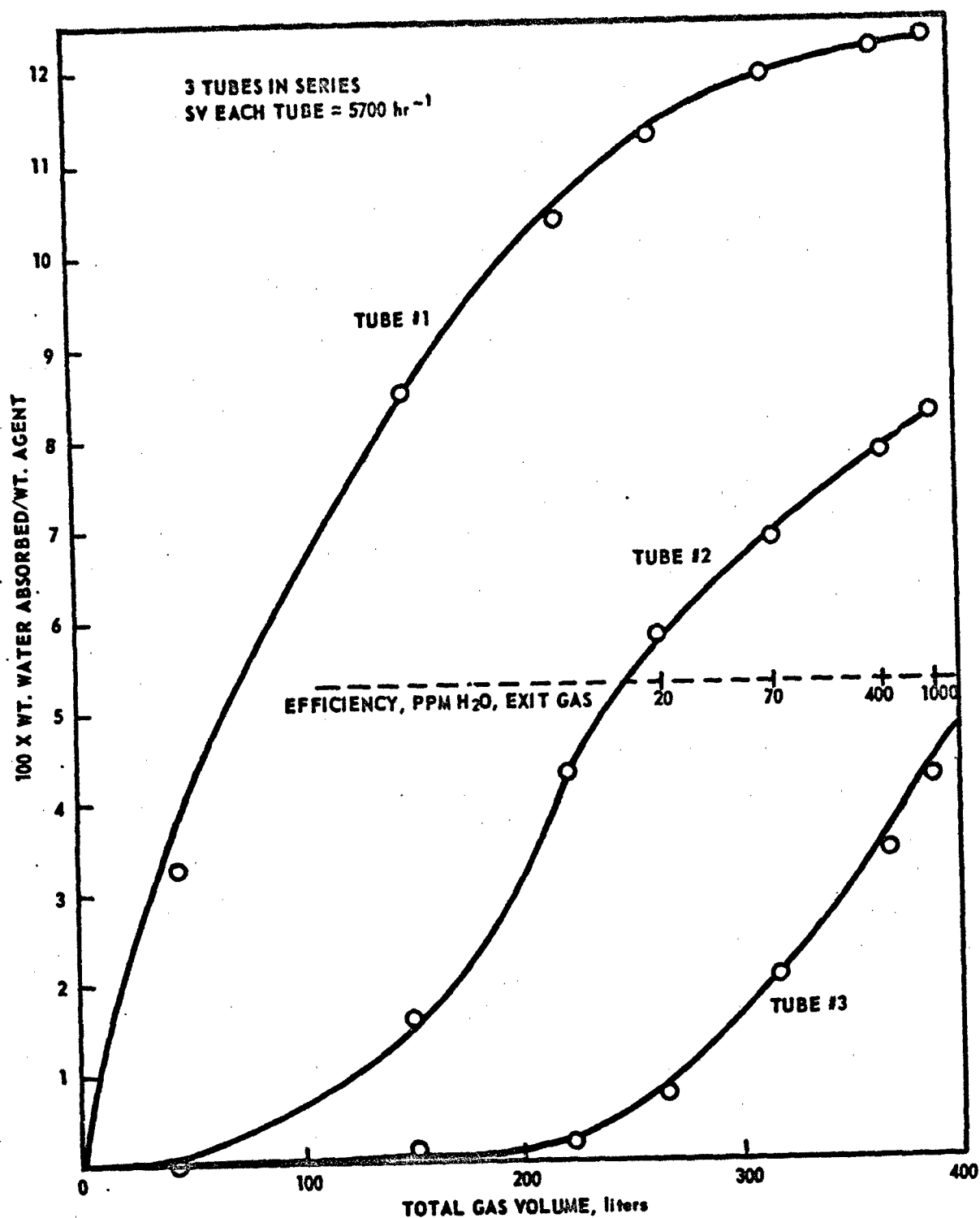


FIGURE 27. DRYING PERFORMANCE OF CALCIUM SULFATE AT 40°C

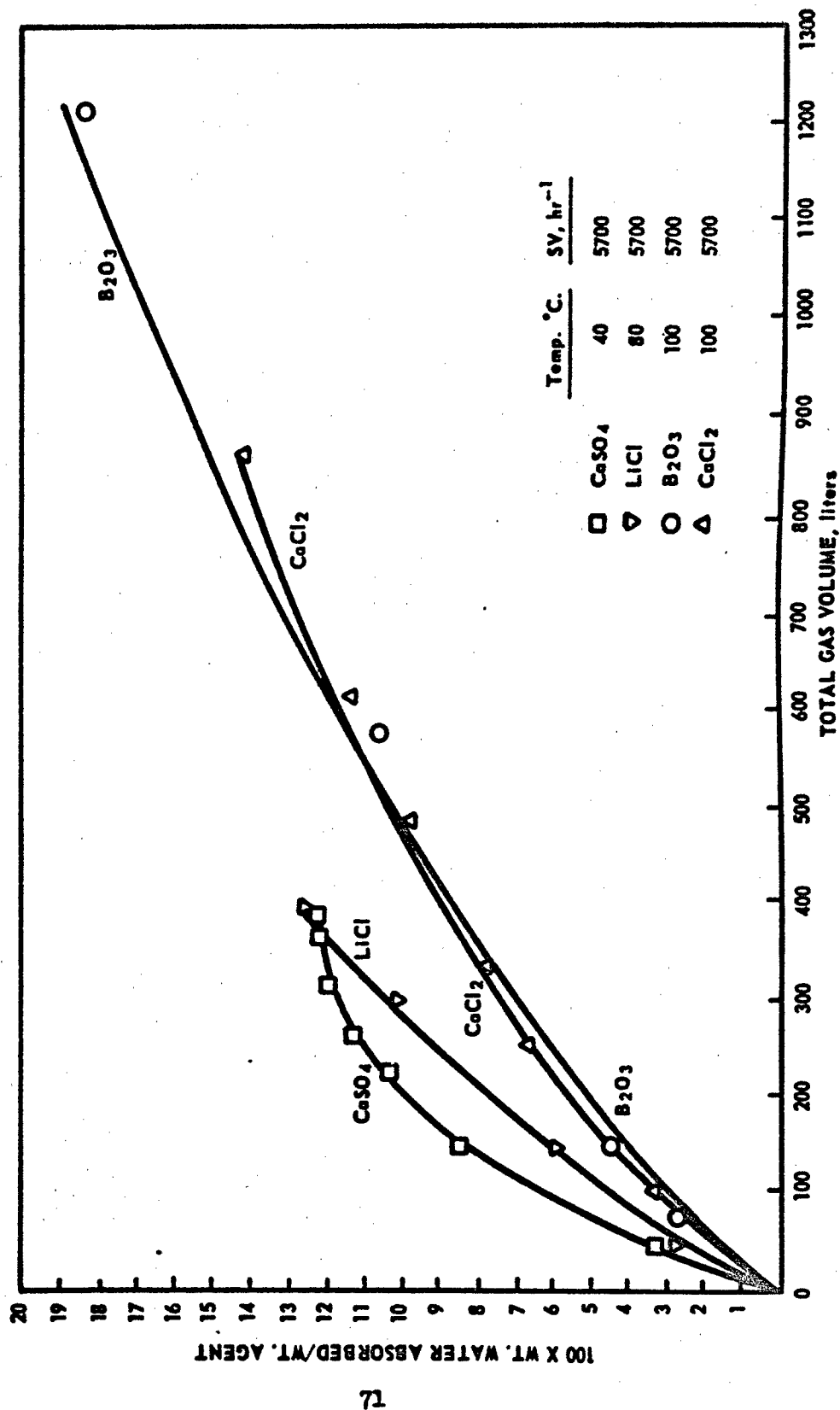


FIGURE 28. ABSORPTION BY VARIOUS AGENTS IN FIRST U-TUBE

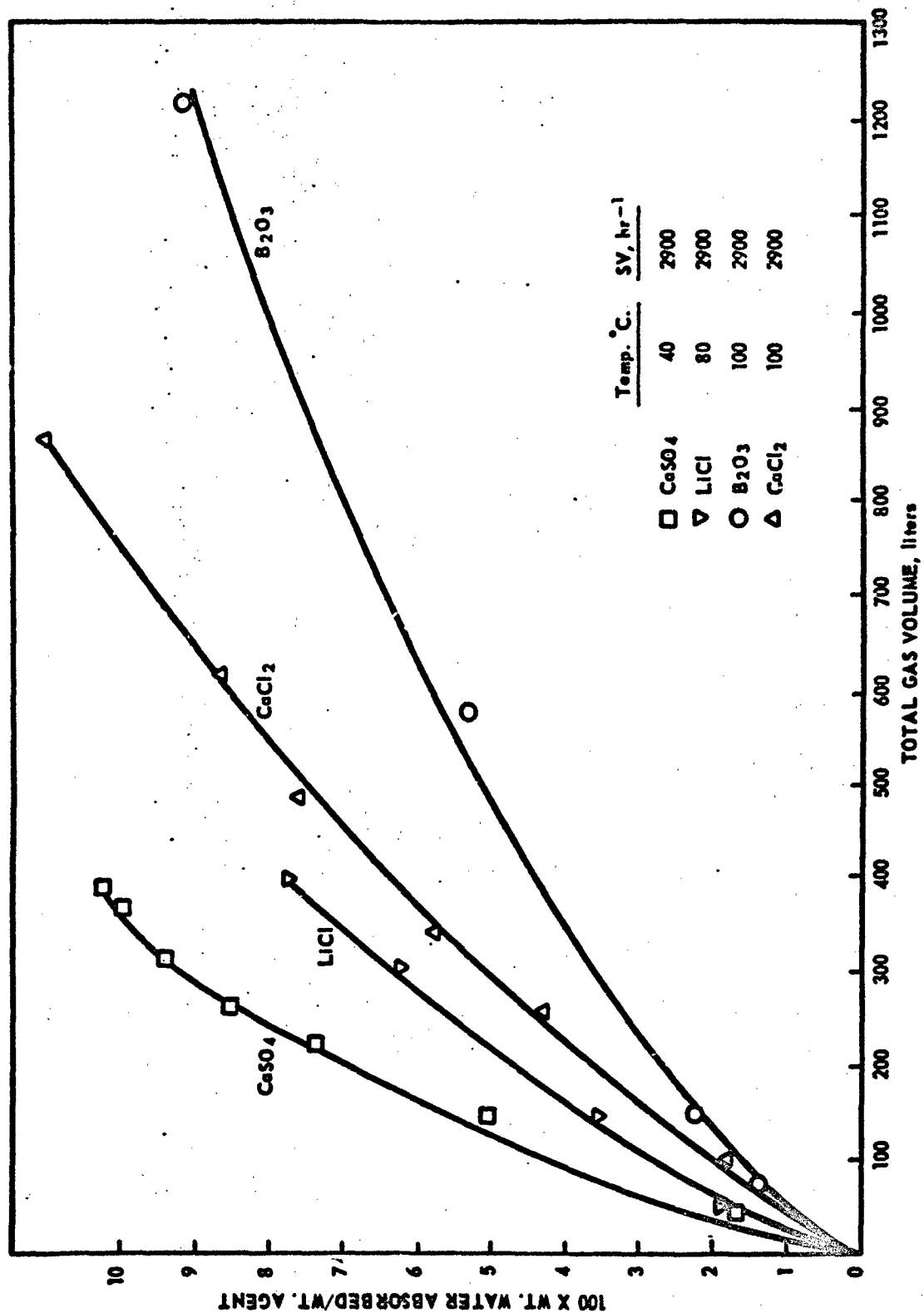


FIGURE 29. ABSORPTION BY VARIOUS AGENTS IN FIRST TWO U-TUBES

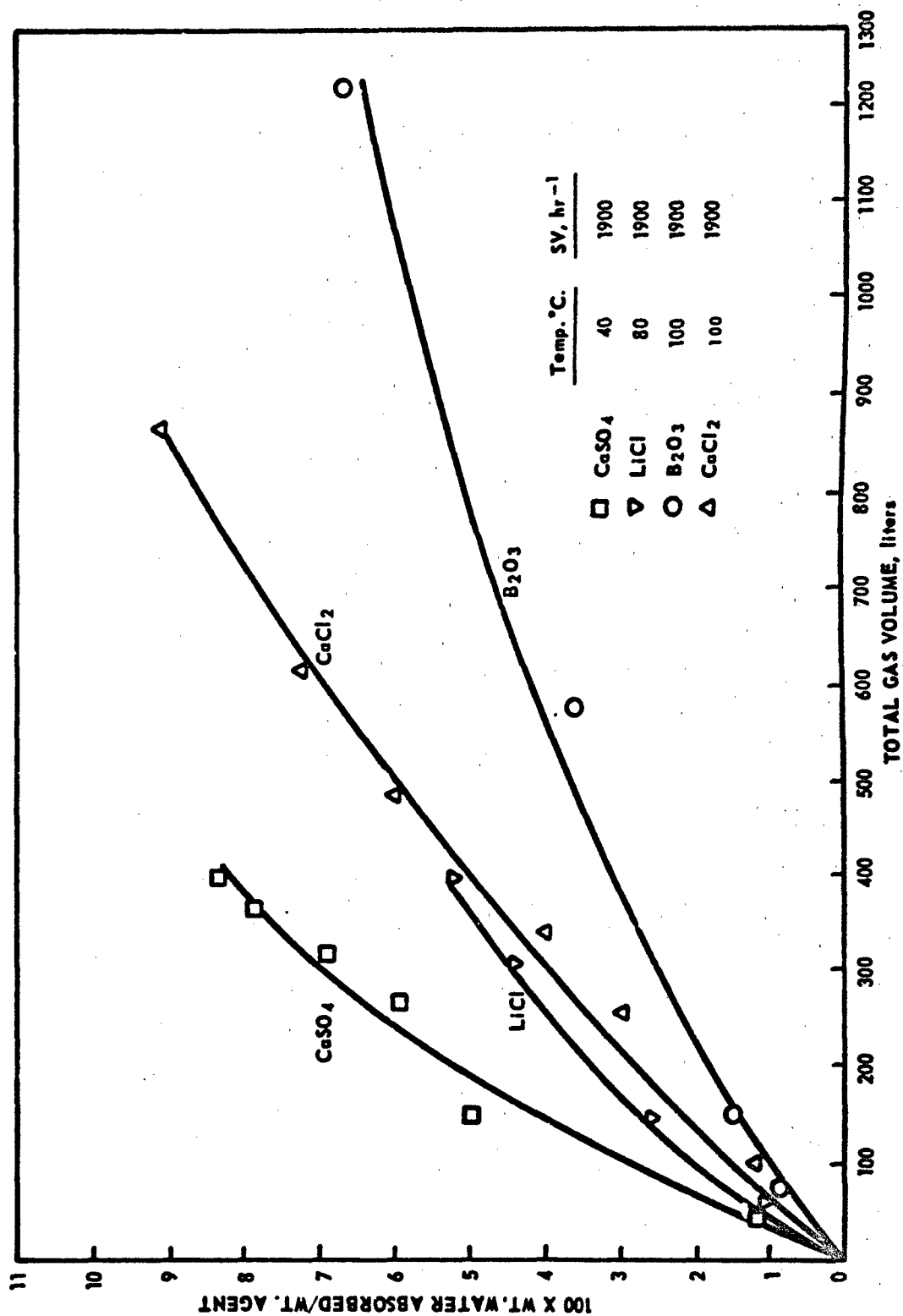


FIGURE 30. ABSORPTION BY VARIOUS AGENTS IN COMPLETE TRAIN

When the performance of CaSO_4 was tested at 100°C . and a SV of $1,900 \text{ hr.}^{-1}$, the hygrometer's upper limit was exceeded, and efficiency data were obtained by water balance using the known volume and water content of the entering gas and the gain in weight of the U-tubes. Up to an average absorption of 1.2% on the agent, efficiency was 9,500 ppm. Between 1.2% and 2.9% absorption, efficiency declined to 31,000 ppm, indicating removal of only 36% of the moisture. Later in the same experiment, hygrometer readings were obtained at 80°C . and 70°C ., showing efficiencies of 910 and 650 ppm, respectively. The last mentioned value was obtained while total absorption on the agent in the system approached 5% by weight.

To further assess the performance of CaSO_4 at elevated temperatures, a run was made in which space velocity was reduced. The absorption bath was held at 95°C ., and the changes in individual U-tube weights were determined over several flow periods. Nitrogen alone was used as the dry gas. To provide a water balance under conditions where the exit water content might be off-scale for the hygrometer, two dry ice/acetone traps and a Drierite trap at 22°C . were connected in series arrangement to the absorption train exit line. All traps were weighed when the U-tubes were weighed. The data permitted a determination of efficiency in relationship to the amount of water picked up by the agent. Results are summarized as follows:

Dry Nitrogen Space Velocity ^m hr. ⁻¹	Accumulated Water on Agent %	Efficiency % Vol.
25	0 -0.4	0.086
400	0.6-1.5	0.40
400	1.5-2.2	0.64
600	0.8-2.0	0.67
600	2.0-3.0	0.80
1200	1.5-3.7	0.97
1200	3.7-5.5	1.78

^mflow rate \div bed volume = space velocity

It can be seen that a significant loss in efficiency took place at an average cumulative water absorption of only about 1%. Even at a space velocity of 25 hr.^{-1} , the 95°C . efficiency up to 0.4% water accumulation averaged 860 ppm, well above the target level for ballast gas entering the aircraft fuel tanks.

(2) Calcium Chloride (CaCl_2)

Calcium chloride was tested at a temperature of 100°C ., where few agents can function with any substantial degree of efficiency. The data obtained for all 3 tubes are shown in Figure 1-D (Appendix D) and lines for CaCl_2 are plotted in Figures 28, 29 and 30.

Even at low absorption levels, the efficiency data in Figure 1-D represent removal of only about two-thirds of the water passing through the train. From the standpoint of capacity, the ability of CaCl_2 to function as a drying agent at this temperature level was demonstrated. The curves in Figures 1-D and 28 provide evidence that this agent continued to absorb water from a flowing stream of wet gas beyond the point where CaSO_4 ceased, despite the temperature penalty of 60°C . The literature⁽¹⁶⁾ indicates that the capacity of solid CaCl_2 may reach 30% at temperatures above 100°C .

(3) Boric Anhydride (B_2O_3)

The performance test with boric anhydride was conducted at 100°C . Data are plotted in Figure 2-D where it is seen that absorption in the first tube followed a pattern very similar to that of the first tube of CaCl_2 . The indicated delay in absorption in the second and third tubes was much greater than in the test with CaCl_2 . In view of the similarity in efficiency and capacity of these two agents at 25°C . (see Table IX), this difference in performance was unexpected. It may be due to a difference in their vapor pressure vs. temperature relationships. A comparison of the efficiency data in Figs. 1-D and 2-D indicates that B_2O_3 was somewhat less efficient than CaCl_2 . Little information was found in the literature concerning B_2O_3 performance at elevated temperatures. Further experimentation with B_2O_3 appears to be needed.

(4) Lithium Chloride

Lithium chloride is dehydrated at 98°C . and 1 atmosphere. For this reason, it was tested at 80°C . At this temperature it was found to be more efficient than either CaCl_2 or B_2O_3 at 100°C ., but less efficient than CaSO_4 at 40°C . Figures 28 to 30 show that it absorbed more water per liter of gas than either CaCl_2 or B_2O_3 , and Figure 3-D shows that the second and third U-tubes began absorbing water early in the test.

(5) Potassium Hydroxide (KOH)

An absorption test with KOH was unsuccessful because of plug formation in the U-tubes. The plugs evidently resulted from melting and freezing of concentrated solutions of KOH , formed at the surfaces of the pellets. No attempt was made to solve this problem in view of the likelihood that KOH will absorb CO_2 as well as H_2O , thus reducing the volume of dry ballast gas and losing some of its capacity to absorb water.

d. Discussion of Results

The data obtained in the tests described above can be analyzed to examine trends and relationships affecting the rate of absorption. This is conveniently done by evaluating $\Delta\%/\Delta V$ as a function of V where:

$\%$ = 100 x weight absorbed ÷ weight of agent

ΔV = an incremental flow of gas

V = cumulative total flow of gas.

This evaluation can be made for the complete absorption train or for an individual U-tube. Data showing changes in the value of $\Delta\%/\Delta V$ during the test made on calcium chloride at 100°C. are plotted in Figure 4-D, with a separate curve being shown for each U-tube in the train. A similar set of curves is shown in Figure 31, where each curve represents the complete train data for one of the agents tested.

It can be seen from Figure 4-D that the rate of absorption in each successive U-tube peaks at a lower value of $\Delta\%/\Delta$ volume, reflecting the lowering of the driving force (partial pressure of water) as the gases progress from one tube to the next. Only the first tube receives a constant feed composition, and the curve for this tube is seen to decline as the capacity of the agent becomes used up. Calcium chloride has a large capacity, however, and a fairly steady rate of absorption was in evidence in Tube No. 1 at the conclusion of the test.

Referring to Figure 31, the curve for B_2O_3 (the other agent tested at 100°C.) is almost entirely a description of what happened in the first tube. The rate of absorption appeared to be stabilized at the 1,200-liter mark, with less than 20% contribution from Tube No. 2, and zero from Tube No. 3. The curve for lithium chloride (at 80°C.) represents less than 25% contribution from Tubes 2 and 3 at the 400-liter mark, and even less percentagewise in the earlier stages of the test, where a high peak rate was achieved. The curve for $CaSO_4$ shows the high rate that would be obtainable if the drying agent could be maintained at 40°C. The drop in efficiency of this agent at the 300+ liter mark caused cessation of the test just prior to the point where the rate would be expected to decline to an extremely low level.

An examination of literature data⁽¹⁷⁾ covering elevated temperature flow tests over $CaSO_4$ show several interesting values, as follows:

Temp. °C.	Space Velocity hr ⁻¹	Accumulated Water Absorption, %	Efficiency % Vol.
60	65	1.8	0.08
65	390	1.0	0.010
65	780	1.0	0.050
65	390	2.0	0.014
65	780	2.0	0.080
70	90	1.5	0.31
100	75	1.0	1.25
100	75	0.5	0.032
110	75	0.6	0.043

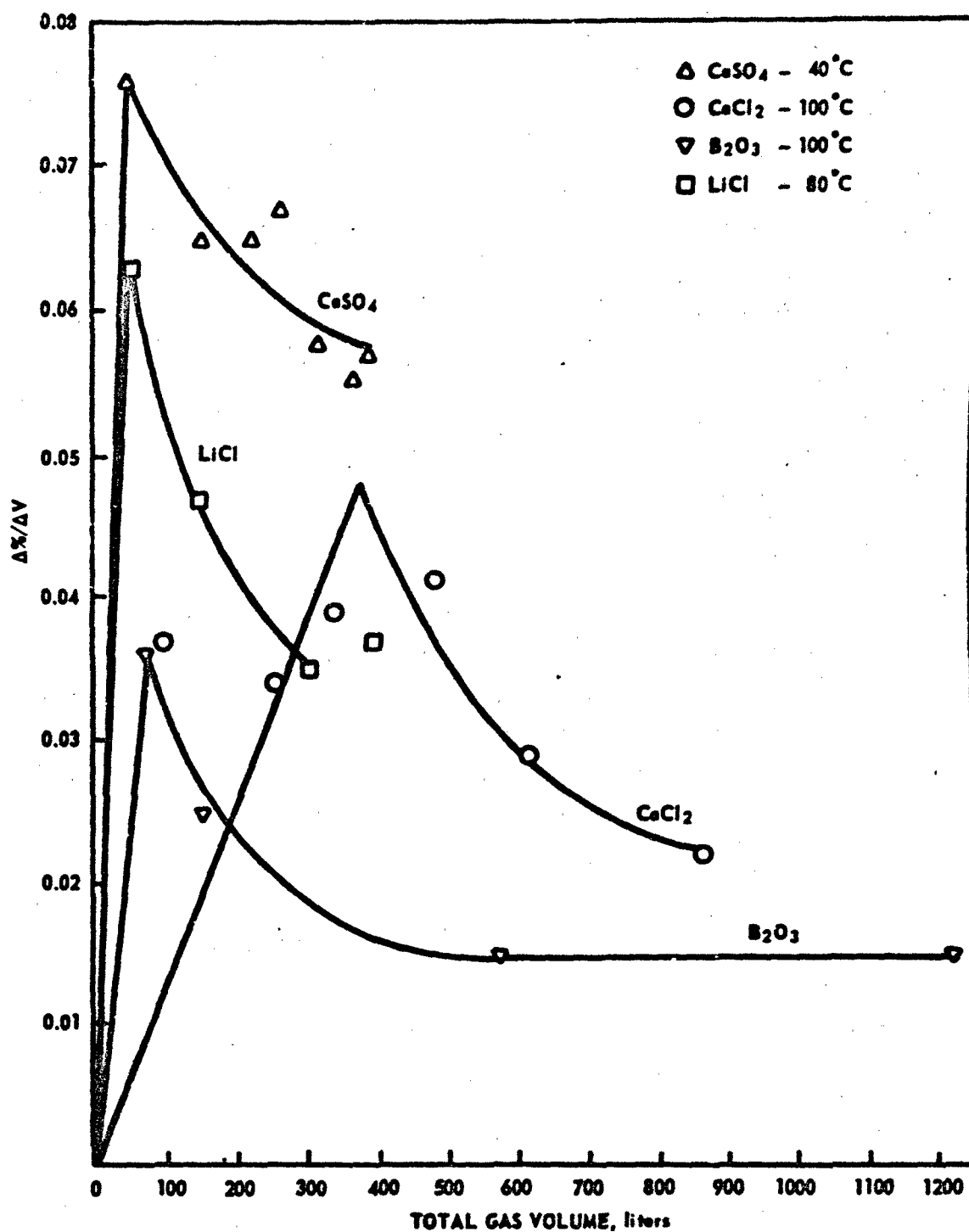


FIGURE 31. WATER ABSORPTION RATE FOR VARIOUS DRYING AGENTS

The 65°C. test results show that efficiency suffers significantly when average accumulation increases in the range of 1-2%, and the results at 100°C. indicate a similar effect.

The following performance design parameters for CaSO_4 at 1 atmosphere pressure and slightly above are assigned based on the experimental and literature data.

<u>Temperature</u>	<u>SV, hr⁻¹</u>	<u>Capacity lb/100 lb</u>	<u>Efficiency % Vol.</u>
100°F (38°C)	1900	5.0	0.002
150°F (65°C)	400	1.0	0.010
200°F (95°C)	24-400	0.5-1.0	0.100

Phosphorus pentoxide, P_2O_5 , has an excellent efficiency, but its volatility could introduce a problem at the elevated temperatures expected in some flight situations. Therefore, CaSO_4 is selected as one high-efficiency agent for this study.

Information received⁽¹⁸⁾ concerning the performance of one of the zeolites (a crystalline adsorbent) indicates the following performance characteristics at 100°F:

Conditions: L/D > 1
linear vel. < 100 ft/min
grain size 1/16" dia. (extrudates)

Performance: efficiency < 10 ppm

capacity 3 lbs/100 lbs

The same source indicates that a 10 ppm efficiency at one-half the above capacity is attainable at 150°F, thus making zeolite an alternate choice for the high-efficiency agent.

Calcium chloride has the best overall performance features for the high-capacity agent in the present application, among those tested. Its large capacity, good absorption rate and ability to remove water over a wide temperature range present a balance of desirable properties, leaving only its limited drying efficiency as a serious drawback. The experimental data for CaCl_2 indicate an efficiency of 1.7% vol. (17,000 ppm) at a temperature of 100°C and a SV of 1900 hr⁻¹. (Pressure was approximately 4 psig.) This is within about 3% of the equilibrium value.⁽¹⁹⁾ It is concluded that for purposes of conceptual design CaCl_2 can be employed at this SV to provide water concentrations within 5% of the equilibrium values, up to a limiting capacity that varies with temperature. Figure 5-D indicates that the limiting capacity is in the vicinity of 30%.

Additional performance tests should be made to more thoroughly characterize the performance of the more promising agents. Of great interest would be the effects of variations in system pressure in the range of 2-50 psia on the important performance characteristics. Given a better insight into the actual bed temperatures and other conditions to be encountered in practice, extended isothermal tests over the full range of operating variables should be made. The results obtained should be used to set up an experimental, two-stage breadboard unit, including provisions for cooling of the beds.

5. EFFECT OF FUEL COMPOSITION

It was originally planned to investigate the effects of fuel vapors on the performance of candidate drying agents. Due to delays encountered in the assembly and checkout of the test apparatus, these tests were not made.

6. REACTION WITH CALCIUM CARBIDE

The reaction of water with calcium carbide to produce acetylene is well known. In the presence of carbon dioxide, a two-step reaction is visualized:



Thus, one mole of CO_2 is lost for each mole of H_2O . The first reaction causes evolution of 2,500 BTU per pound of water, and the second one produces 4,400 BTU per pound; therefore, total heat evolution equals 6,900 BTU/lb.

The quantity of calcium carbide required for the reaction, at the stoichiometric ratio, equals 3.55 lbs./lb. water converted. A larger amount of carbide must be estimated to allow for the surface deposit of CaCO_3 , which would block access of the gas to unreacted carbide and, in a flow system, to allow for adequate contact time. An additional consideration is the need for distributing the reaction over sufficient volume to allow transfer of the reaction heat to cooling coils.

If a calcium carbide reactor is used, the loss of ballast gas volume due to absorption of CO_2 is readily calculated. For example, removal of 0.1% (1,000 ppm) water would be accomplished by loss of a similar volume of CO_2 , which can be neglected even if it is assumed that all of the acetylene dissolves in the fuel.

SECTION V

CONCEPTUAL DESIGN

1. GENERAL

The performance targets set forth in the contract are stated in Section I (Introduction). The following discussion presents a general description and analysis of the conceptual inerting subsystem that satisfies these targets, and at the same time interacts satisfactorily with the demands and services of the main system (aircraft). Detailed discussions of the design and function of the principal components are presented. Finally, the conceptual design criteria are applied to specific flight missions in order that the performance benefits can be related to penalties in weight and volume.

2. PRELIMINARY ANALYSIS

a. General Description

A simplified flow diagram of the inerting subsystem is presented in Figure 32, which indicates the main components. These are described very briefly as follows:

(1) Fuel Tank

This represents all the tanks on the aircraft, which are interconnected. This is the delivery point for the ballast gas generated in the inerting subsystem.

(2) Fuel Vaporizer and Fuel/Air Mixer

A small fraction of the aircraft fuel is drawn off, at a controlled rate, to an atomization and vaporization unit. The diagram indicates admixture with combustion air in the same unit, although various mixing schemes are possible.

(3) Air Preheater

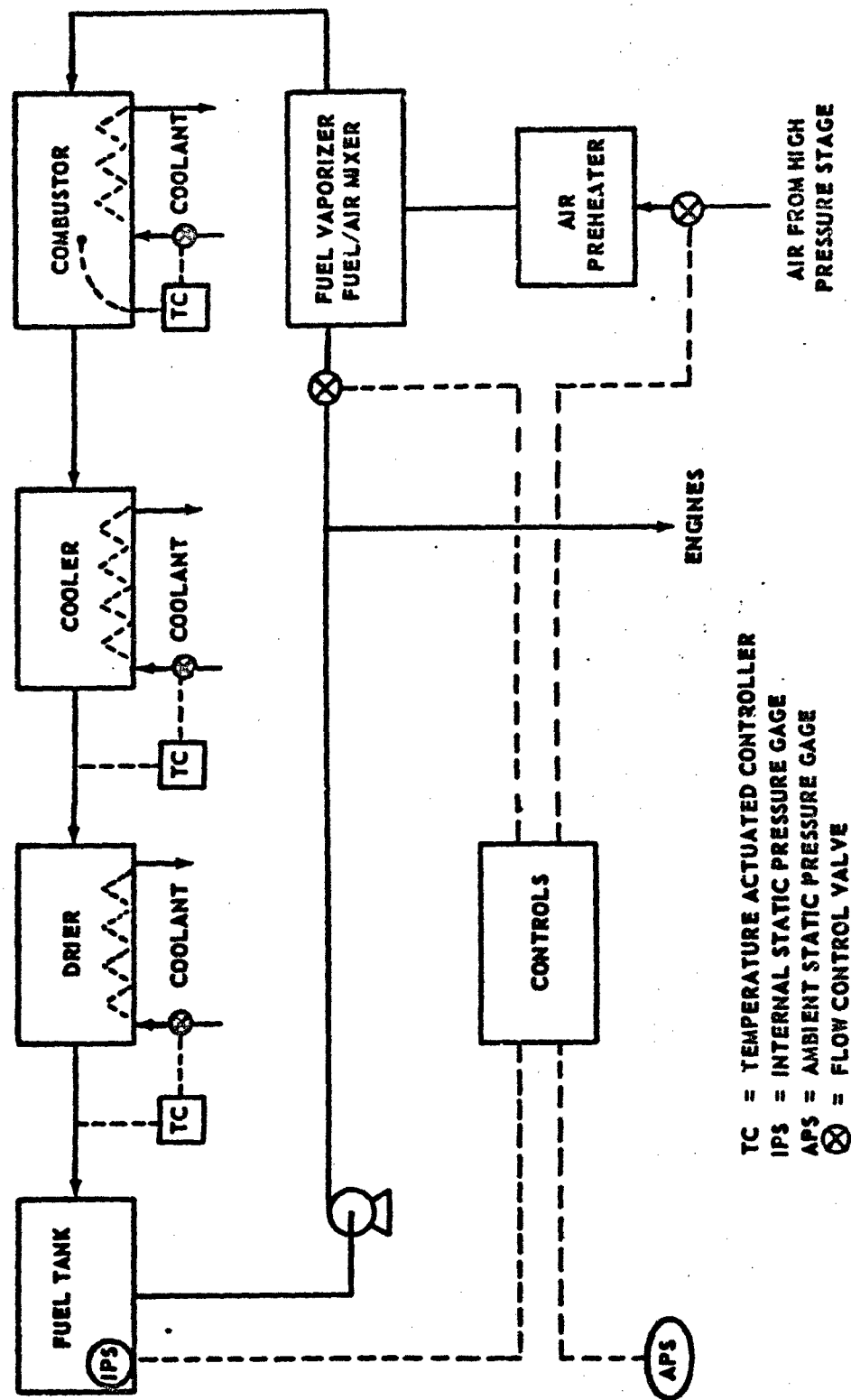
Air for combustion in the inerting subsystem is drawn from the engine compressors, and is given the necessary amount of additional heat in this unit.

(4) Combustor

The catalyzed combustion process takes place in this unit. Combustion heat must be removed in order to prevent overheating of the catalyst, but combustion temperatures are far below those existing in non-catalytic combustors.

(5) Cooler

Heat is removed from the combustion products in order to facilitate separation of the water of combustion.



TC = TEMPERATURE ACTUATED CONTROLLER
 IPS = INTERNAL STATIC PRESSURE GAGE
 APS = AMBIENT STATIC PRESSURE GAGE
 ⊗ = FLOW CONTROL VALVE

FIGURE 32. SIMPLIFIED DIAGRAM OF INERTING SUBSYSTEM

(6) Drier

Cooled combustion gases are passed through this unit, containing a drying agent, which removes water from the gases before they are admitted to the fuel tank.

(7) Controls

The controls regulate flows of fuel, air and coolants in order to maintain a sufficient flow of dry ballast gas, and to maintain the proper operating conditions.

The seven components mentioned above can be grouped conveniently into three major elements: Combustor, Drier and Controls. Reference will be made to these in the discussion which follows.

b. Feed Streams

(1) Air

Air can be drawn from the engine compressors, or from the engine exhaust stream. The latter would be hotter but would exist at a lower pressure. The higher pressure source is preferred because more energy is provided to drive the gases through the subsystem to the fuel tanks. Demand varies as a function of both fuel consumption rate and ambient pressure change. The latter is important because most aircraft fuel tanks are designed to maintain a maximum positive differential pressure of only 2-4 psi relative to ambient, and even less on the negative side.

The concept of scooped air is rejected because of interference with the aerodynamic performance of the aircraft, and because such air would be available at lower pressures than compressor air.

The rate of flow of air into the system is governed by the demand of the fuel tank(s) for ballast gas, transmitted via the controls.

(2) Fuel

The aircraft fuel is used as the fuel for the inerting subsystem. Its temperature varies during the flight mission, increasing towards the end of a supersonic flight, the exact amount of increase depending on whether or not the tank is insulated, and whether or not the fuel is circulated to cool some other subsystem on the aircraft. Fuel pressure in the transfer line normally runs in the vicinity of 25 psi above ambient. Flow of fuel is governed in relationship to flow of air to maintain the desired fuel/air ratio.

c. Combustor

(1) Preheating of Air

The heat requirements vary according to the air flow rate and initial temperature, also the temperature required for fuel vaporization and for the combustion process itself. A number of air heating methods are possible, including combinations:

- (a) use as coolant in catalyst bed
- (b) use as coolant for gases that have exited from the combustor
- (c) separate preheater utilizing engine exhaust, electric power, or indirect exchange (coil) with engine combustion chamber. Only by means of a separate preheater can one provide hot air for startup of the system.

(2) Preheating of Fuel

Preheating of the fuel contributes to improved atomization and vaporization performance, and to the efficiency of the combustion reaction. The hot combustion gases leaving the catalyst bed can be used as a source of heat. Piping of fuel through coils embedded in the catalyst is rejected because of the likelihood of excessive wall temperatures and fouling of the surfaces. During startup, a separate preheater is required. A line heater using electrical resistance elements is the most likely choice.

(3) Fuel Atomization and Vaporization

There are several methods that seem worthy of consideration.

(a) Carburetor

Provided it would function under all flight attitudes and over the required range of air flow rates, this is an attractive method of atomization because it occupies little space and functions very simply.

(b) Mechanical Atomizer

A rotary mechanical atomizer can be used to cover a wide range of fuel flow rates, but involves equipment with high-speed moving parts. Alternatively, a two-fluid nozzle can be used, wherein air at moderately high pressure is required.

(c) Injection

Depends on availability of a booster pump. Fuel at high pressure can be injected through a nozzle into a turbulent flow of hot air, and sufficient contact provided for the vaporization process to be completed.

Of the various alternatives, the two-fluid nozzle is chosen based on simplicity of design and operation.

(4) Catalytic Reactor

(a) Preheat

The reactor must be capable of reaching operating temperature quickly. Among the possible methods of warmup are use of a stream of hot engine exhaust, use of a small pilot reactor that can be ignited cold and run long enough to heat the main reactor, and use of electrical resistance heaters. The latter method is selected for conceptual design.

(b) Flow Rate

Flow of ballast gas varies widely during a mission. This variation can affect:

- (i) degree of conversion
- (ii) pressure drop and pressure
- (iii) temperature profile
- (iv) possible shortage of heat if conversion lags.

These effects are anticipated in the conceptual design. Such techniques as the use of recycle streams and staged or parallel reactors have advantages for this type of situation.

(c) Pressure

A high pressure in the reactor favors the reaction rate constant, and a low pressure drop provides margin for additional losses before the ballast gas enters the fuel tank. The pressure drop across the reactor is a function of catalyst grain size, which also affects conversion. Thus, choice of grain size is a trade-off situation in the ultimate design.

(d) Temperature Control

Excessive temperature damages the catalyst via thermal deactivation, and too low a temperature causes low conversion of oxygen. The heat of reaction is very large, and steep temperature gradients build up within the bed unless the spacing between cooling surfaces is minimal. Tubing coils, possibly finned, can be used within the bed. The coolant fluid within the coils might be air, water or fuel. Of these, fuel has the disadvantage of potentially fouling the tube wall. Water has the disadvantage of being not required except for cooling, and thus represents another item to be carried on the aircraft, but its vaporization requires so much heat that it merits strong consideration.

(e) Conversion Level

This is a function of:

catalyst type and amount
catalyst activity level (age, coke)
temperature
pressure
flow rate
fuel-air ratio

(f) Servicing

A hydrocarbon conversion catalyst must be regenerated periodically in order to remove the coke which is deposited when operating under stoichiometric or fuel-rich conditions. The catalyst reactor is designed for quick removal and replacement by a serviced unit, but it is also feasible to carry out regenerations using a ground-service truck with appropriate connections to the aircraft.

(g) Design Concepts

There are several approaches to the design of this reactor. These are as follows:

(i) One Reactor With Recycle

A portion of the exit gas is recycled (requires a booster) in order to provide a constant space velocity throughout the flight.

(ii) Two Reactors

Two reactors are connected in parallel so that, by valving and switching, the flow can be routed to one or the other, or both, depending on the demand for ballast gas.

(iii) Variable Volume Reactor

This concept calls for a single reactor designed to open up a variable number of sections to the flow of gases, depending on ballast gas demand. Various mechanisms can be visualized for activating the sections on demand.

(iv) Single Reactor Without Recycle

This is the simplest arrangement. The flow of gas through the bed of catalyst varies in proportion to ballast gas demand, causing variations in the quantity of combustion heat released. Reflecting these changes will be variations in temperature profile and flow of coolant.

Primarily because of its simplicity, the last mentioned scheme is selected for the present study.

d. Drier

(1) Cooler

Wet gases leave the combustion zone at a temperature in the order of 700-750°C., and may or may not be cooled below this level by exchange within the combustion unit itself. Regardless, additional cooling is needed to bring the temperature low enough for water removal. Several media can be considered:

- fuel enroute to the engines
- combustion air enroute to the combustor
- fuel enroute to the combustor.

Because of the high wall temperatures encountered, fouling of the surfaces must be a consideration, and air has an advantage over fuel.

The cooler reduces the gas temperature enough for satisfactory drier performance. (If water is condensed, provision must be made to separate and remove it.) Control of temperature is achieved via a thermocouple in the exit gas stream, which is linked to a coolant flow control valve. Design of the cooler is affected by choice of coolant, temperature and pressure of coolant, and allowable pressure drop in ballast gas.

(2) Water Absorber

A portion of the water is removable by condensation from the wet ballast gas, depending on the availability of a satisfactory coolant. Condensation has the advantage of saving on heat duty for heat of reaction between water and drying agent, and also saves on the weight of agent required. Balanced against this is the weight of the condenser and associated equipment. Ballast gas containing non-condensed water is directed to a vessel packed with a solid, granular drying agent(s). Design and performance of this drier is a function of the absorbing agent's properties:

grain size
efficiency
capacity
regenerability
chemical compatibility

Two agents arranged in series are used, the first with high capacity and the second with high efficiency.

The quantity of agent(s) in the drier is a function of the maximum permissible exit water content, the drier temperature, absorbent characteristics (above), and the flow rate and pressure of ballast gas during the peak demand period. It is also governed independently by the total amount of water to be absorbed during a mission, or from one regeneration to the next. Design is influenced by the allowable pressure drop and by possible undesirable effects of unreacted fuel vapors. It is necessary to design the drier for ease of regeneration in place, or ease of removal.

The supply of coolant to the drier removes the heat of condensation, heat of reaction, and adjusts the sensible heat of the ballast gas to the permissible level for entry into the fuel tank. The general unavailability of low-temperature coolants on high-speed aircraft, and the importance of temperature with respect to the efficiency of drying (see Section IV), indicate need for a supply of cooling water. Water flowing through coils in the drier makes it possible to keep the temperature at 200°F. or below.

Controls directly associated with the drier include:

- check valve on outlet line to prevent flow from fuel tank into drier
- temperature sensor linked to coolant flow control valve.

Indicating instruments for monitoring include a hygrometer for final moisture content, and a gage showing pressure drop across the drier.

e. Controls

(1) Principles

- (a) quick response to changing demand
- (b) constant fuel/air ratio, within allowable limits
- (c) limited change in conversion due to variations in flow through the combustor catalyst bed
- (d) protection against overheating of catalyst and combustor
- (e) emergency provisions, allowing for instrument malfunction
- (f) minimum water content in ballast gas
- (g) supremacy of mission and aircraft over the inerting subsystem

(2) Approaches

(a) Sensors

All sensors must be sensitive, reliable, and capable of responding at all accelerations, altitudes and attitudes over the necessary range.

- (i) Demand relating to changing ambient pressure is sensed by means of pressure transducers, one in the fuel tank and one located to measure ambient static pressure.
- (ii) Demand relating to fuel consumption is sensed by a flow sensor or sensors.
- (iii) Demand relating to oxygen content of ballast gas is sensed by a sensor located in the exit line of the drier.
- (iv) Demand for coolant flow to the cooler and drier have already been mentioned. Demand for coolant flow to the combustor is to be sensed by thermocouples placed at strategic internal locations. In all cases where coolant flows are involved, coolant inlet and outlet temperatures will be measured, and control of coolant flow may be subject to control to prevent coolant temperatures from exceeding stipulated limits. In some cases, flow of coolant may be regulated to provide a minimum change in ballast gas temperature.

(b) Control Elements

In general, signals from the various sensors are received, amplified as necessary, and used to actuate control mechanisms on valves. There are several possible schemes:

(1) Direct

All controls are actuated directly and independently.

(ii) Indirect

One item, such as the air control valve, is actuated, and the setting of this valve and flow rate is the basis for adjusting the setting of the fuel flow control valve and (if used) the controls that maintain constant space velocity.

(c) Special Considerations

(i) Air Flow

There is a wide range of adjustment to be made in ballast gas flow, reflecting the difference between cruise during level flight and a powered dive. Two air control valves may be necessary, one for low demand and one for high demand. (If two air supply lines are indicated, two preheaters and air-fuel mixing chambers may be required.)

(ii) Fuel Flow

Fuel may be taken from the transfer line to the engines, in which case a flow control valve in the diversion line is adequate. If a separate fuel pump and line are used, control may involve either:

- flow control valve on exit line from centrifugal pump, or
- regulation of speed and/or stroke of a fixed displacement pump.

(iii) Fuel Tanks

It is essential that the tanks be prevented from failure by either bursting or collapsing. Therefore, when the difference between tank pressure and ambient static pressure exceeds a certain level (tank on the negative side), and the supply of ballast gas fails to prevent a further increase in this difference, a breather valve of adequate capacity opens with sufficient speed to prevent tank wall failure. This same valve closes again as soon as the pressure difference returns to a safe level, and does not reopen unless the indication of inadequate flow from the inerting subsystem is repeated.

On ascents, some flushing of the tanks to remove oxygen originally present is desirable. Therefore, the inerting subsystem is set to deliver ballast gas at a certain minimum level at all times, and the tank vent valve bleeds off sufficient air to maintain tank pressure at a safe level above ambient.

3. COMBUSTOR

a. Design Choice

(1) Radial Reactor

Of the various alternatives, a single reactor of the radial design offers the advantages of a low pressure drop, a flow front that increases with increasing radius, and a configuration that simplifies construction problems. The gas stream, moving radially outward from a cylindrical core, contacts the catalyst, absorbs the heat of reaction, then transfers the heat to finned coils which run parallel to the long axis of the reactor and are embedded in the catalyst. These coils contain water which vaporizes in the

cooling process. The mixture of preheated fuel vapor and air is distributed uniformly along the central core, and passes through wall perforations into an annular chamber where it is mixed with the remainder of the preheated combustion air. This mixture then passes through wall perforations to enter the bed of catalyst. A grid of resistance heating elements is located at the entrance to the catalyst bed for use during startup operations. Gases that have passed through the catalyst bed leave through a perforated cylindrical tube wall and enter a chamber where they encounter a finned coil containing combustion fuel requiring preheat. The gases then enter a heat exchanger (HE 1), which may or may not be integral with the catalytic reactor, where combustion air is preheated. The combustor is depicted in Figures 33 and 34. The radial reactor is selected for the SST design calculations.

(2) Segmented Reactor

This type of reactor is described in Figure 35. Its distinguishing characteristic is the alternate placement of layers of catalyst and banks of finned cooling coils. Provision against possible preignition is made by addition of the combustion air in increments. This configuration lends itself more readily than does the radial design to the use of naked cooling coils, and thus to the elimination of inert diluent in the catalyst bed. (As developed in Section V-6 for SST Flight Plan No. 1, in excess of 100 pounds of diluent were required to submerge the cooling coils.) The segmented reactor presents the possibility of more efficient heat transfer because of the radiation effect, but this potential advantage has not been estimated as a part of the present study. The segmented reactor design is chosen for the tactical aircraft, and details are given in Section V-7.

(3) Air and Fuel Preheat

Both are preheated by exchange with hot combustion gases. Details are presented in Sections V-6 and V-7.

(4) Fuel Vaporization and Mixing

A two-fluid nozzle is used for atomization of the fuel. The atomizing fluid is preheated air equal to 2% of the combustion air, and yields a mixture containing 80% fuel. The conical spray from the nozzle enters a diverging section where vaporization is completed, then the mixture is converged and delivered through a connecting pipe to the combustor. The walls of the chamber are heated by resistance heaters. Details are given in Section V-6. Selection of this design was based largely on mechanical simplicity.

b. Operation

The above equipment is operated at conditions imposed by the aircraft, the flight mission, and the catalyst. After startup (see above), the catalyst bed temperature is regulated by control of cooling water flow rate in the coils. Design calculations are based on the use of 1/16" x 1/8" Code A catalyst maintained at 1337°F. (725°C). After startup, the temperature of fuel preheat is regulated by reducing the power to the resistance heaters at the vaporization chamber, and under peak fuel demand conditions it is expected that the power input to these heaters will be minimal. Similarly, the air preheat temperature will be controlled by regulating the power input to the heating elements located in the annular compartment of the combustor inlet line, with a major reduction in power taking place after the startup period.

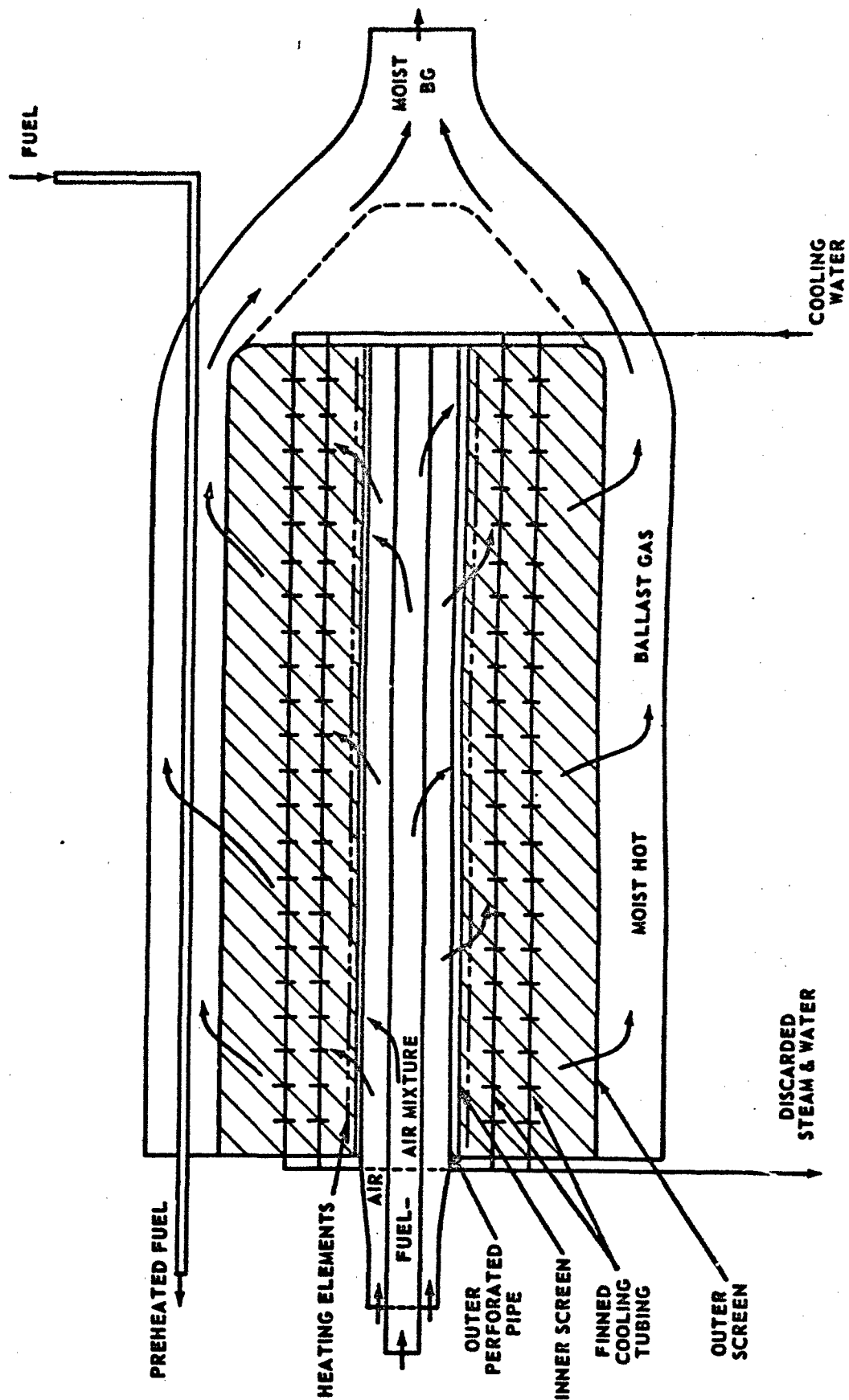


FIGURE 33. LONGITUDINAL CROSS-SECTION OF RADIAL COMBUSTOR

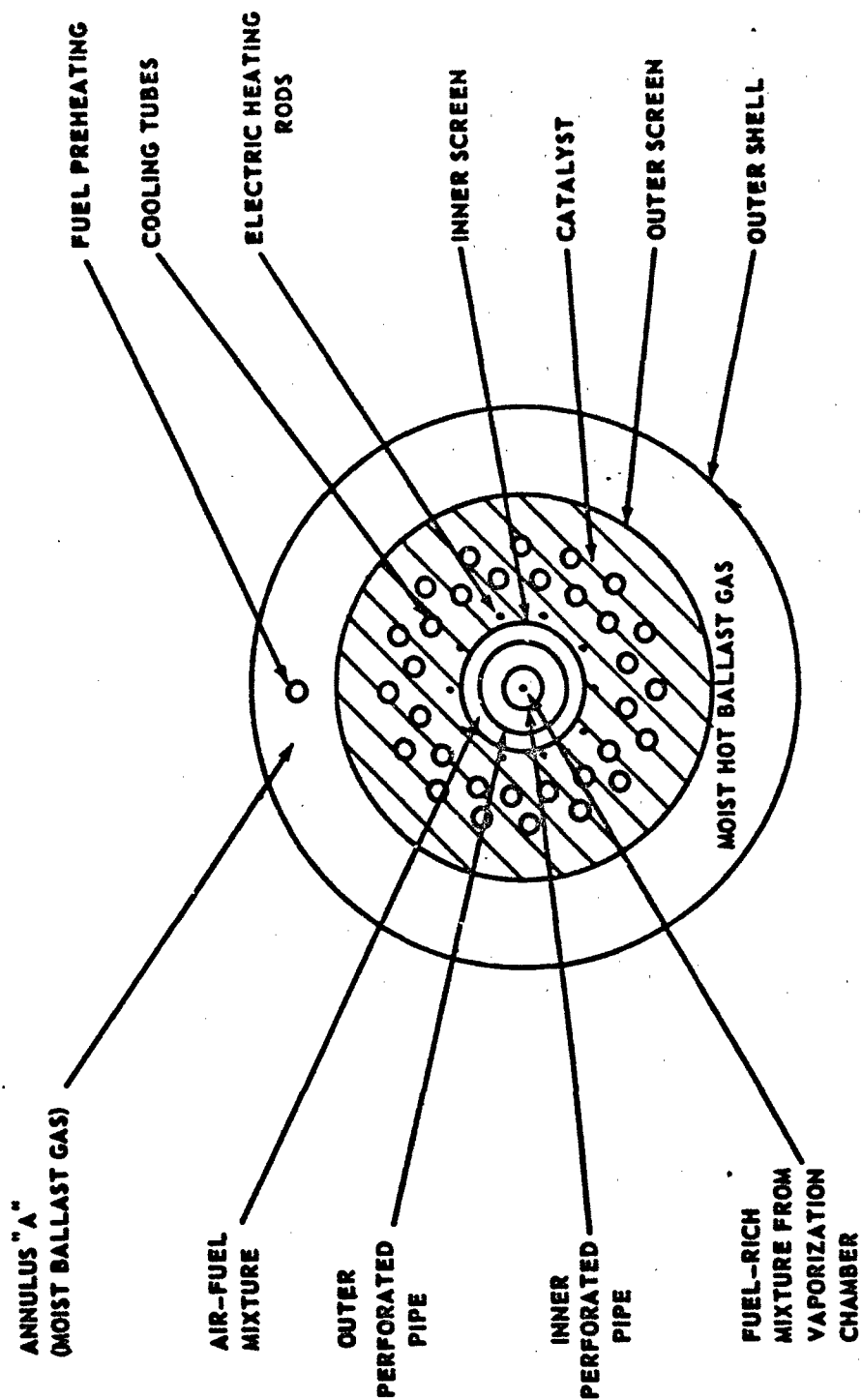


FIGURE 34. TRANSVERSE CROSS-SECTION OF RADIAL COMBUSTOR

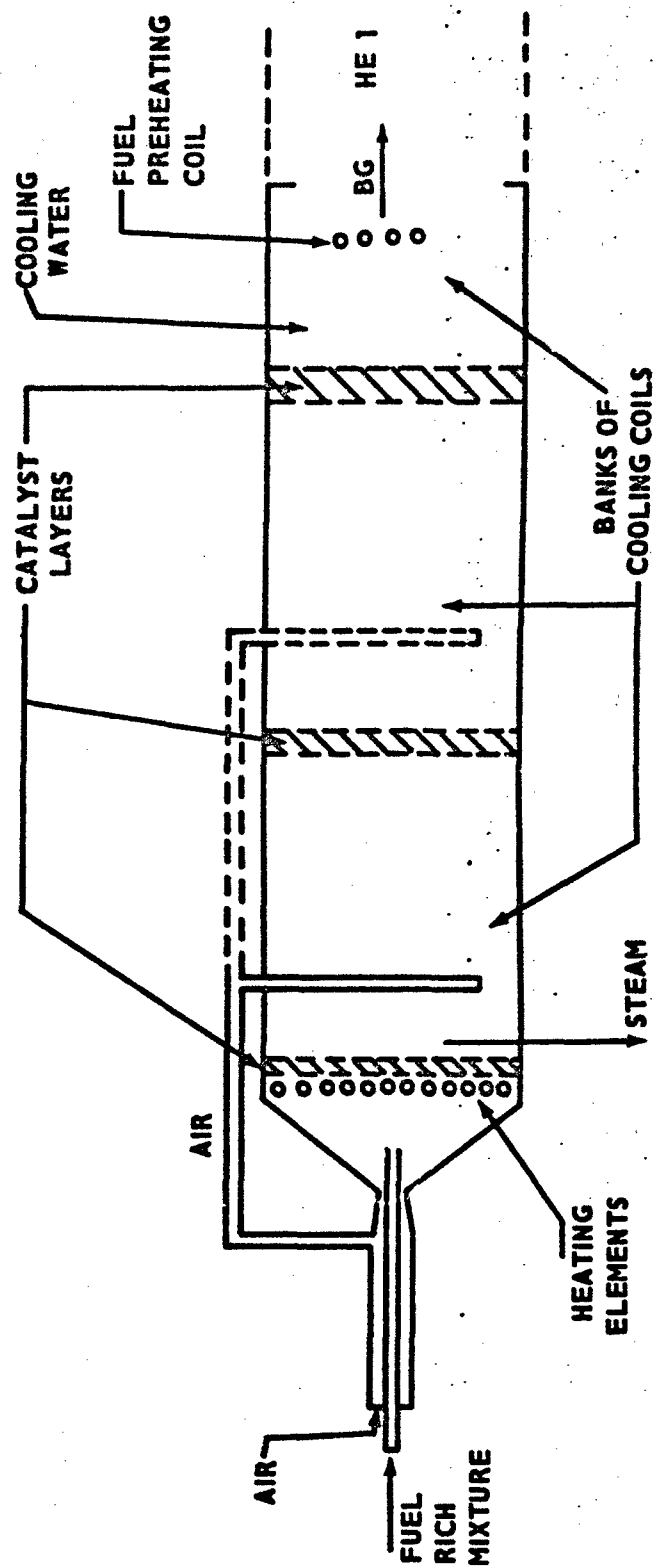


FIGURE 35. SCHEMATIC DIAGRAM OF SEGMENTED COMBUSTOR
(LONGITUDINAL SECTION)

Because of the benefit to reaction rate of an excess of fuel in the mixture, a 10% excess was chosen. Operation for periods of at least 60 hours without regeneration is anticipated, even if larger excesses of fuel are employed.

c. Amount of Catalyst

Based on experimental results with JP-7, Code A catalyst is used at a temperature of 725°C (1337°F). Despite the excess of fuel, the conservative assumption is made that the reaction rate constant found for the stoichiometric mixture applies:

$$k = 194,000 \frac{\text{ft}^3 (\text{reactant mixture})}{\text{ft}^3 (\text{catalyst}) \times \text{hr.}}$$

The volume of catalyst to use (for first order reaction) is given by (20):

$$V_c = \frac{F_{AO}}{k C_{AO}} \int_0^{X_A} \frac{1 + E_A X_A}{1 - X_A} dX_A$$

which upon integration yields

$$V_c = \frac{F_{AO}}{k C_{AO}} \left[(1 + E_A) \ln \frac{1}{1 - X_A} - E_A X_A \right]_0^{X_A} \quad (A)$$

and the weight of the catalyst is obtained by

$$W_c = \rho_c V_c$$

The meaning of the symbols used is:

k = reaction rate constant, $\text{ft}^3 (\text{fluid})/\text{ft}^3 (\text{catalyst}) \cdot \text{hr.}$

V_c = volume of catalyst, ft^3

F_{AO} = feed rate of Component A, lb-moles A/hr.

Component A = oxygen

C_{AO} = initial concentration of Component A, lb-moles A/ ft^3 mixture

X_A = conversion of Component A, moles A reacted/moles A

W_c = weight of catalyst, lb.

ρ_c = specific weight of catalyst, lb./ ft^3

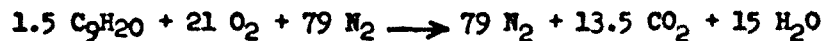
E_A = fractional change in volume due to reaction

(1) Determination of E_A

$$E_A = \frac{\text{No. of moles leaving} - \text{No. of moles entering}}{\text{No. of moles entering}}$$

(and the number of moles leaving is a function of conversion)

For stoichiometric reaction and 100% conversion of oxygen:^m



$$E_A = \frac{(79 + 13.5 + 15) - (1.5 + 21 + 79)}{(1.5 + 21 + 79)} = \frac{107.5 - 101.5}{101.5} = 0.05911^m$$

For 10% excess fuel and 100% conversion^m

$$E_A = \frac{107.65 - 101.65}{101.65} = 0.05903^m$$

Values of E_A for a few selected conditions are summarized, together with the evaluation of the integral in (A) for the same, in Table X.

For calculation of the catalyst volume we have chosen to express the flow rates at the conditions adopted as standard in our experimental program, which were:

$$t = 72.5^\circ\text{F.} \quad \text{and} \quad P = 14.7 \text{ psia}$$

as a convenience in the calculations. However, the design of individual components in the subsystem (including the combustor) is based on the actual conditions existing in the components.

Where V_2 is the volume at experimental conditions,

$$\begin{aligned} V_2 &= V_1 P_1 \frac{532.5}{660 \times 14.7} \\ &= V_1 P_1 \times 0.0549 \end{aligned}$$

The volume of 1 mole of gas at the experimental conditions is:

$$\frac{14.7}{492} \times 359 \times \frac{532.5}{14.7} = 388.5 \text{ ft}^3/\text{lb.-mole.}$$

^mUsing JP-7. Assumed equivalent composition = C_9H_{20} , and molecular weight = 128.

TABLE X. VALUES FOR CALCULATING QUANTITY OF CATALYST

Fuel: JP-7				
Amount of Fuel	X_A = Conversion	% O ₂ in Dry Ballast Gas	E_A	$\frac{[(1+E_A)\ln \frac{1}{1-X_A} - E_A X_A]_0^{X_A}}{0}$
Stoichiometric	1.000	0.00	0.0591	∞
10% excess	1.000	0.00	0.0590	∞
"	0.980	0.53	0.0578	4.082
"	0.960	1.05	0.0567	3.348
"	0.750	5.53	0.0443	1.415
"	0.619	8.33	0.0365	0.978

The calculations for determination of amount of catalyst to use are as follows:

- (a) Determine the dry ballast gas demand at $200^{\circ}\text{F} = \text{B.G.}$
- (b) Ballast gas requirements are converted into air demand at the same conditions, assuming the stoichiometric reaction and removal of all water:

$$V_1 = 1.081^{\text{m}} \times \text{B.G. cfm}$$

- (c) Determine the pressure = P_1 in the fuel tank, at design conditions.
- (d) The actual conditions, as listed above, are now converted to the experimental conditions, and the equivalent flow rate = V_2 (at experimental conditions) is obtained:

$$V_2 = 0.0549 \quad V_1 P_1 \quad \text{cfm}$$

- (e) Molar flow rate of air = N_{Air} in number of moles of air per minute is calculated by dividing the equivalent flow rate by the molar volume of air at experimental conditions (388.5 ft³/lb-mole)

$$N_{\text{Air}} = V_2 / 388.5 \quad \text{lb.-moles air/min.}$$

- (f) Molar flow rate of oxygen, N_{O_2} , is 21% of the molar flow rate of air.

$$N_{\text{O}_2} = 0.21 N_{\text{Air}} \quad \text{lb.-moles/min.}$$

- (g) Oxygen feed rate, F_{AO} , per hour is obtained by multiplying above by 60

$$F_{\text{AO}} = 60 N_{\text{O}_2} \quad \text{lb.-moles/hr.}$$

- (h) Molar flow rate of fuel, N_{F} , is determined by multiplying the molar flow rate of air by 0.0165^m (because for each 100 moles of air we require 1.65^m moles of fuel, including 10% excess).

$$N_{\text{F}} = 0.0165^{\text{m}} N_{\text{Air}} \quad \text{lb.-moles/min.}$$

- (i) To obtain the weight flow rate of fuel, W_{F} , the molar flow rate of fuel is multiplied by its molecular weight (128 lb./lb.-mole)

$$W_{\text{F}} = 128^{\text{m}} N_{\text{F}} \quad \text{lb./min.}$$

^mFor JP-7.

- (j) The specific volume of fuel vapor at the experimental conditions is found from⁽²¹⁾:

$$V_{\text{vapor}} = \left[\frac{0.242 (t + 460)}{P} \right] \left[\frac{1.03 - d}{d} \right] \text{ ft}^3/\text{lb.}$$

for: $t = 72.5^\circ\text{F.}$

$P = 14.7 \text{ psia}$

$d = 0.7990 \text{ g/ml at } 60/60^\circ\text{F}$

$\therefore V_v = 2.55 \text{ ft}^3/\text{lb. fuel}$

- (k) The flow rate of fuel vapor becomes

$$V_F = 2.55 \text{ ft}^3/\text{min}$$

- (l) Total volumetric flow rate of gases is the sum of air and fuel vapor flow rates

$$V_T = V_2 + V_F \text{ cfm}$$

- (m) Initial oxygen concentration, C_{AO} , in the air-fuel mixture is calculated by

$$C_{AO} = \frac{N_{O_2}}{V_T} \text{ lb-moles } O_2/\text{ft}^3 \text{ mixture}$$

- (n) The integral in Equation (A) is evaluated at the desired conversion level.

- (o) The feed rates of oxygen (F_{AO}) are specified.

- (p) The specific weight of catalyst is chosen (40.5 lb/cu. ft. for Code A catalyst).

- (q) The weights and volumes of catalyst corresponding to specific conversion levels and feed rates of oxygen are calculated.

- (r) The space velocity at any of the situations can be calculated:

$$SV = \frac{60 V_T}{V_c} \text{ hr}^{-1}$$

d. Size of Equipment

Rather than present a generalized method of sizing the preheaters, vaporization and mixing chamber, and catalytic reactor, the method will be illustrated below in Sections V-6 and V-7 where application is made to specific cases.

²¹For JP-7.

e. Safety

One potential safety problem that requires close attention is that of ignition and combustion at any point previous to the catalyst bed. Based on literature information(22), the upper limit of flammability of mixtures of this fuel with air at the expected temperature of 600°C. is 8.4% (volume) of fuel. In the radial reactor, premature combustion is avoided by admixing initially only that amount of air required for good atomization. Not until this fuel-rich mixture (80% fuel)* passes beyond the perforations in the wall of the central core is the rest of the combustion air admixed. In the segmented reactor, the additional air is added in increments, as indicated in Figure 35. (One or more flame arrestors might be necessary, but are not shown in the figure.)

f. Logistics and Servicing

In concept, the catalytic reactor portion of the combustor requires periodic attention for regeneration of the catalyst, which does not require its removal from the reactor, and for eventual replacement with a fresh charge.

Regeneration requires heating the catalyst to a temperature at which the coke will burn off in the presence of a gas mixture containing approximately 4% oxygen. The required temperature is in the vicinity of 400°C. It is unlikely that the ignition grid will enable the reaction to be sustained throughout the bed; therefore, a source of hot gases containing 4% oxygen is required, or a hookup permitting circulation of a 400°C. heating fluid through the cooling coils must be provided. Technically, it is feasible to set up for either of these methods while the reactor is in place and the aircraft on the ground, using a ground service truck. It is also feasible to disconnect and remove the catalytic reactor from the aircraft and substitute a unit containing regenerated or fresh catalyst. This would allow the regeneration to be carried out on a schedule independent of the aircraft flight mission schedule. The gases issuing from the unit during regeneration are vented, except for a bleed sample used to determine completion of the process (analysis for CO₂ and/or O₂).

Replacement of the catalyst is estimated at intervals of from 500 to 1,000 hours of service. This operation requires removal of the reactor unit from the aircraft, opening of a loading port, and removal of the used catalyst from the reactor. In the radial design, a simple dumping removes nearly all of the catalyst, but some may remain lodged between the fins of the cooling coils and requires special attention such as use of a blast of clean compressed air. Filling of the reactor with fresh catalyst is done carefully to achieve uniform packing. A vibrator machine is used for this purpose, and weight records are maintained as an indication of the packing density.

*At this concentration, only "cool flame" combustion is a possibility.

b. GAS DRIER

a. Design Choice

(1) Drier

Design is directed toward the closest practical approach to equilibrium efficiency, and reflects the necessity of restricting the pressure drop to approximately 25% of the total difference between the air supply and the fuel tanks. It has been stated⁽²³⁾ that a contact time of 10 seconds (equivalent to a space velocity of 360 hr^{-1}) is in general industrial use, and that superficial velocities used in practice range from 30 to 60 fpm where a close approach to equilibrium efficiency is sought. The performance test data obtained in our program indicate that even at equilibrium the water content of the ballast gas exceeds target conditions; hence, small space velocities (large drier beds) may be required, and a radial flow configuration is unlikely. A simple packed bed is chosen for this study. Although its shape in cross-section can be varied to conform to the available space, a rectangular cross-section is selected. The bed contains finned cooling coils to receive the heats of condensation and absorption, and to insure the lowest possible temperature in the downstream portion of the drier. A descriptive diagram is given in Figure F-9, Appendix F.

(2) Gas Coolers

The moist ballast gas leaving the combustor must be cooled before entering the drier. The first significant cooling occurs in HE-1, where heat is exchanged with the incoming combustion air. Exit temperature from HE-1 is limited by the temperature of the inlet air, which varies during the mission and is assumed to average 600°F . in a normal flight.

Next, the moist ballast gas enters HE-2 where it gives up heat to the aircraft fuel being pumped to the engines. Fuel temperature varies during the mission, and fuel may be used for other cooling assignments. In the Tactical Aircraft situation, the fuel is cool enough to condense water from the ballast gas and lower the temperature into the region where significant drying can be done. In the SST situation, the average inlet fuel temperature is 300°F , and therefore an additional exchanger (HE 3) is added. HE 3 uses a special supply of cooling water, which makes it possible to condense a portion of the water in the ballast gas, and to lower the temperature of the gases entering the drier into the region where water can be absorbed. The inlet cooling water temperature varies from 40° to 80°F during the flight, and an average temperature of 65°F is assumed.

(3) Cooling Water Supply

A tank and pump are required to hold and deliver cooling water to the gas cooling units and to the gas drier itself. The tank is sized to contain sufficient water for the entire mission, plus 10% contingency. It operates at ambient pressure, and has electrical heaters to prevent freezeup. The pump is of the centrifugal type, and discharges through flow control valves to the drier and (for the SST) to exchanger HE 3.

b. Operation

The above equipment operates at conditions that provide maximum cooling, hence maximum removal of water from the ballast gas. When the engines are at or near idle speed, compressor air temperature is 250°F., and this provides a lower-than-design BG temperature entering HE-2. When the fuel temperature is at its lowest level, a similar benefit is experienced at the inlet to HE-3 (SST) or the drier (tactical). Also, when cooling water temperature is below the design level, more water can be condensed in HE 3 (SST) and absorbed in the drier. The flows of coolants to all of these units are regulated to provide a specified change in BG temperature and, to further increase overall performance, cooling water flow is never reduced below a selected level designed to provide coolant over the entire flight.

During startup of the subsystem, the first gases passing through the combustor contain excessive free oxygen, and these can be vented to the atmosphere until the catalyst bed temperature control (or other sensor) indicates design conversion is achieved. The temperatures in the coolers and drier will rise as the combustion gases flow through them, causing the efficiency of drying to decrease from an initial high level to the design level. Provision is made to drain all water condensed in these units.

c. Drying Agents

(1) Selection

As per Section IV, CaCl_2 is selected as the high-capacity agent and, depending on temperature, CaSO_4 or a zeolite as the high-efficiency agent. The amount of each agent in the bed is based on consideration of its bulk density, efficiency and capacity, and the desire for design performance efficiency over a maximum period between regenerations.

An alternate scheme for consideration utilizes a back-up unit charged with calcium carbide, to insure reaching the target moisture level.

(2) Amounts

The following procedure provides a simplified approach to the dual agent arrangement:

- (a) Both agents are assumed to be present in the same bed, with the gases passing first through the high-capacity agent, second through the high-efficiency agent.
- (b) The quantity of each agent is calculated independently, using the design space velocity value and the volume flow rate at the pressure and temperature conditions in the drier.
- (c) The design capacity of each agent at the conditions in the drier is used to determine the number of flights or flight-hours of service between regenerations. This calculation is made using the amount of water removed in the drier as determined under average conditions.

- (d) If the number of flight-hours for both agents equals or exceeds 50, no further calculations are made. If the number is less than 50 in either case, the weight and volume of agent is increased proportionately to provide the target 50 hours of service.
- (e) If the number of flight-hours of service exceeds 50 in the case of the high-efficiency agent, but not in the case of the high-capacity agents, the capacity equivalent of the excess hours is credited to the high-capacity agent in order to minimize the total weight.

The bulk density data employed in the calculations are as follows:

CaSO ₄	75 lb/ft ³
CaCl ₂	51 lb/ft ³
zeolite	38.5 lb/ft ³

d. Size of Equipment

The transverse area is chosen to provide a superficial velocity in the recommended range. Otherwise, conventional guidelines are followed. Details for specific situations are given in Sections V-6 and V-7.

e. Safety

There are no noteworthy safety problems relating to the coolers and gas drier. The agents have been selected to avoid problems from contact with any unreacted fuel that may be present.

f. Logistics

Because of its low cost, calcium chloride is commonly used once and discarded; however, logistics considerations may indicate the necessity of a regeneration treatment. For this reason, the level of hydration should be limited to a weight gain of 30 lbs/100 lbs of CaCl₂ (the monohydrate), which would not liquefy under regeneration conditions. It is assumed that regeneration involves the procedure used for CaSO₄, which follows.

Regeneration of calcium sulfate is a common industrial practice. The usual procedure⁽¹⁷⁾ is to pass a stream of gas heated to 450°F through the bed until the exit temperature reaches 400°F. Steam may be moved through the coils in the bed to speed the process. Application of this procedure to the inerting subsystem may involve removal of the drier from the aircraft to a regenerating facility equipped with either an air heating or a 250 psig steam service; or it may involve connections from the aircraft to a ground vehicle equipped with one of these services. In either case, removal of the agents from the drier is deferred until such time as a rise in pressure drop or other indication of performance decline shows it to be necessary.

Regeneration of the zeolite is similar to the above procedure, except that the hot gas is heated to a temperature of approximately 550°F⁽¹⁸⁾, and the exit gas temperature on completion is about 500°F.

If a calcium carbide reactor is included as part of the drier, the carbide reactor is designed for easy recharging of this one-shot agent. A cartridge unit is contemplated. A new or recharged unit is inserted at the time when a spent unit is removed from the aircraft. Care is taken in the design of equipment and facilities to prevent exposure of the carbide to the atmosphere. Thus, planning provides for either a sealed throw-away cartridge requiring no re-packaging in the logistics channel, or a field re-packaging station where cartridges removed from the aircraft are emptied and recharged. In the latter instance, special procedures and moisture exclusion equipment are required.

5. HEAT AND MATERIAL BALANCE

Essential to the design of this subsystem are the balances covering heat and materials, because these establish the flows and conditions at various points in the subsystem. In place of a detailed, generalized scheme covering all of the inputs and outputs for any aircraft and mission, a detailed example of the calculations is presented in Appendix E, which applies to the situation described in Section V-6 below.

6. CASE ANALYSIS I - SUPERSONIC TRANSPORT

a. Basis

For the purpose of this analysis, certain assumptions are made concerning the capacities and operating characteristics of the SST, as follows:

Fuel tank capacity: 30,000 gallons = 4,010 ft³
 Fuel tank pressure: ambient plus 2 psi
 Initial vapor space: Zero or 10% capacity \approx 0 or 400 ft³
 Final vapor space: 90% capacity \approx 3,610 ft³
 Flight time: 3 hours
 Maximum fuel rate: $R_m = 3 R_c$
 Cruising fuel rate: R_c
 Maximum fuel rate applies for 20% of flight.

Use of JP-7 fuel is assumed.

Two flight plans were selected for analysis. Table XI describes Flight Plan No. 1, in which the SST makes a 3-hour trip that includes a 20-minute full-power ascent following takeoff, a cruise at 75,000-80,000 feet, and a gradual descent preparatory for landing. This plan is substantially in line with published information⁽²⁾. The second flight plan, in Table XII, starts off the same but is terminated by an emergency, powered dive in which the rate of pressure increase reaches 14.7 psi/min.

At various periods during these flights, the demand for ballast gas to pressurize the fuel tanks may be radically different, there being four distinct situations:

- Cruise with no change in altitude
- Normal descent (20 min. duration) with a maximum pressure change rate of 1.4 psi/min.
- Powered dive (of 0.5 min. duration) with a maximum pressure change rate of 14.7 psi/min.
- Ascent, during which displacement rate is reduced because of the expansion of gas already in the tanks as ambient pressure decreases.

b. Fuel Flow Rates

For the purpose of this calculation, a normal 3-hour flight is assumed, and it is also assumed that the vapor space in the tanks is 0% at the start, 90% at the finish.

TABLE XI. FLIGHT PLAN NO. 1, SUPERSONIC TRANSPORT

Fuel Tank Capacity 30,000 Gallons

No.	Operating Period		Engine Power	Altitude (m ft)		Ave. Rate Climb [Descent] (m/fpm)	Ambient Conditions		Fuel Load (% C'py)	Est'd Fuel Temp. (°F)
	Duration (min.)	Description		Start	End		Press. (atm)	Temp. (°F)		
1	0	Take off	full	0	0	---	1.000	60	100, 90	60
2	20	Accel. and climb	full	0	66	3.3	0.045	-69		
3	30	Gradual climb	cruise ⁺	66	75	0.3	0.040	-69		
4	100	Level flight	cruise	75-80	75-80	0	0.040	-69		
5	10	Prepare for descent	cruise ⁻	80	55	[1.5]	0.085	-69		
6	20	Descent and landing	idle	55	0	[2.75] ^(a)	1.000	60	10	135-250 ^(b)
	180									

(a) Maximum rate of pressure increase is 1.4 psi/min. (during final minute).

(b) Depends on insulation of fuel tanks; see References 2 and 24.

TABLE XII. FLIGHT PLAN NO. 2, SUPERSONIC TRANSPORT

Fuel Tank Capacity 30,000 Gallons

No.	Operating Period		Engine Power	Altitude (m ft)		Ave. Rate Climb [Descent] (m/min)	Ambient Conditions		Fuel Load (% C'py)	Est'd Fuel Temp. (°F)
	Duration (min.)	Description		Start	End		Press. (atm)	Temp. (°F)		
1	0	Take off	full	0	0	---	1.000	60	100, 90	60
2	20	Accel. and climb	full	0	66	3.3	0.045	-69		
3	30	Gradual climb	cruise ⁺	66	75	0.3	0.040	-69		
4	106	Level flight	cruise	75-80	75-80	0	0.040	-69		
5	0.5	Powered dive	full	80	17	[126] ^(a)	0.527	-1		
6	1.0	Gradual dive	full	17	1	[16]	0.966	55		
7	0.5	Approach	idle	1	0	[2]	1.000	60		
8	0	Landing	idle	0	0	0	1.000	60	10	135, 250 ^(b)

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(a) Maximum rate of pressure increase is 14.7 psi/min. (between 80,000 and 17,000 ft.).

(b) Depends on insulation of fuel tanks; see References 2 and 24.

$$(3 \text{ hrs}) (0.2 R_m + 0.8 R_c) = 30,000 \times 0.9 \text{ gal.}$$

$$R_m = 3 R_c$$

thus

$$0.2 R_m + 0.8 R_c = 27,000 \div 3 \text{ gal/hr}$$

$$0.2 (3 R_c) + 0.8 R_c = 9,000 \text{ gph}$$

$$1.4 R_c = 9,000 \text{ gph}$$

$$\begin{aligned} R_c &= 6,430 \text{ gph} \approx 860 \text{ cfh} \\ &= 107 \text{ gpm} \approx 14.3 \text{ cfm} \end{aligned}$$

$$\begin{aligned} R_m &= 19,290 \text{ gph} \approx 2,580 \text{ cfh} \\ &= 322 \text{ gpm} \approx 43 \text{ cfm} \end{aligned}$$

c. Ballast Gas Flow During Ascent

In general, flow of gas to the fuel tanks is expressed at a temperature of 200°F. (the estimated temperature of gas in the tanks), and ambient static pressure plus 2 psi. Gas flows to all components of the inerting system are adjusted to correspond to the conditions in those components.

(1) No Initial Vapor Space (BG_1)

To replace the consumed fuel (R_m) it is necessary to supply 43 cfm. However, because of the reduction in ambient pressure during ascent, the tank pressure must undergo a similar reduction. For a very high altitude flight, the total change in pressure on ascent approximates 14.7 psi, and during a 20-minute ascent the pressure change in each minute is 1/20 of this, hence 0.7 psi. This means that all of the gas present in the tank at the end of the n th minute expands 5% in the $(n + 1)$ th minute, decreasing the volume to be added (at ambient conditions) by $43/20 = 2.15$ cf. Thus, for each minute of climb, the flow rate of ballast gas varies as per

$$BG_1 = 43 - 2.15 \int_0^n dn \text{ cfm}$$

where n = number of minutes elapsed from start of climb.

In this way, ballast gas flow rate changes from 43 cfm during the first minute to 0 during the last minute.

(2) Initial Vapor Space = 10% FT Capacity (BG_2)

3,000 gal = 400 cf initial ullage

Normally, the amount of gas vented during ascent would be:

$$\frac{400 \text{ ft}^3}{\text{min.}} \times \frac{0.7 \text{ psi}}{14.7 \text{ atm}} = 20 \text{ cfm}$$

Instead of venting this gas, allowance could be made for its expansion in calculating ballast gas requirements:

$$BG_2 = \left(43 - \int_0^n 2.15 \, dn \right) - 20$$

$$BG_2 = 23 - 2.15 \int_0^n dn \text{ cfm}$$

(An alternate approach, not calculated here, would be to ignore the venting of the initial ullage gas and utilize the full 43 cfm of ballast gas to expedite the purging of oxygen from the tank.)

In the assumed situation, whether or not there is any initial vapor space, when the point is reached where the volume deducted to allow for expansion of the gas already in the tank equals the volume pumped to the engines, the flow of ballast gas is continued at the cruise rate. This is done for two reasons: to avoid shutting down the inerting system, and to reduce the oxygen content of gases in the ullage space.

d. Ballast Gas Flow During Cruise (BG_3)

During the cruise part of flight, the altitude changes (and consequently the P changes) are negligible, and it is only necessary to replace the consumed fuel, hence 15 cfm of ballast gas is required.

$$BG_3 = 15 \text{ cfm}$$

e. Ballast Gas Flow During Descent

(1) Normal Descent (BG₄, BG₅)

During a slow descent (engines are idling), which is assumed to take 20 min., the average rate of pressure change (increase) is 0.7 psi/min., the maximum rate of pressure change is 1.4 psi/min., the vapor space is 90% of FT capacity, and the fuel consumption is about 1/5 that of cruise rate or 3 cfm. As an approximation, the total pressure change is 14.7 psi.

Thus, the ballast gas demand is:

(for average ΔP , BG₄)

$$\frac{0.9 \times 30,000 \text{ gal}}{\text{min.}} \times \frac{0.7 \text{ psi}}{14.7 \text{ psi}} \times \frac{\text{atm}}{7.48 \text{ gal}} \times \frac{\text{ft}^3}{\text{ft}^3} + 3 = 183 \text{ cfm}$$

$$\boxed{BG_4 = 183 \text{ cfm}}$$

(for maximum ΔP = the design value, BG₅)

$$\frac{0.9 \times 30,000 \text{ gal}}{\text{min.}} \times \frac{1.4 \text{ psi}}{14.7 \text{ psi}} \times \frac{\text{atm}}{7.48 \text{ gal}} \times \frac{\text{ft}^3}{\text{ft}^3} + 3 = 363 \text{ cfm}$$

$$\boxed{BG_5 = 363 \text{ cfm}}$$

(2) Powered Dive (BG₆)

Assumed to last 0.5 min., during which the pressure change rate is 14.7 psi/min. and the maximum fuel consumption rate applies. Vapor space is 90% of FT capacity.

Ballast gas demand due to pressure change is:

$$\frac{0.9 \times 30,000 \text{ gal}}{\text{min.}} \times \frac{14.7 \text{ psi}}{14.7 \text{ psi}} \times \frac{\text{atm}}{7.48 \text{ gal}} \times \frac{\text{ft}^3}{\text{ft}^3} = 3,610 \text{ cfm}$$

$$\text{Total ballast gas flow rate} = 3,610 + 43 = 3,653 \text{ cfm}$$

$$\boxed{BG_6 = 3,653 \text{ cfm}}$$

f. Amount of Water to Remove

The following was developed in Section V-3:

- one mole of dry ballast gas requires 1.081^m moles of combustion air
- one mole of water is produced by the combustion of 1.4^m moles of oxygen

First, the total flow of ballast gas during the flight is computed, and this is used to calculate the flow of combustion air and the average pressure of the ballast gas as delivered.

(1) Flight Plan No. 1, No Initial Vapor Space

It is determined that after 13 minutes of ascent the BG₁ value reduces to 15 cfm. During the remaining 7 minutes of ascent, the flow of ballast gas is maintained at cruise rate (15 cfm). Referring to Table XI, periods 3, 4 and 5 are lumped together as a period of level flight. This simplification does not introduce any significant effect in the calculations that follow:

$$\text{Ascent: } \left[\sum_{n=0}^{n=13} \left(43 - 2.15 \int_0^n dn \right) \right] + (20-13) \times 15 = 512 \text{ cf}$$

$$\text{Cruise: } [180 - (20 + 20)] \times 15 = 2,100 \text{ cf}$$

$$\text{Descent (normal): } 183 \times (14.7/0.7) = 3,843 \text{ cf}$$

$$\text{Total Ballast Gas} = 6,455 \text{ cf}$$

$$6,455 \times 1.081 = 6,980 \text{ cf combustion air}$$

Total Combustion Air = 6,980 cf

The above volumes have not been adjusted to a common pressure. For this purpose, a mean flight pressure can be calculated by dividing the sum of the volume x pressure value for all periods in the flight by the total volume (above). There are two major periods, one of constant pressure and one of changing pressure (climb and descent). The average pressure for the latter is obtained by dividing the area under the ambient pressure vs. altitude curve (this area is calculated by graphical integration and is equal to 344,160 psia-ft) by the altitude difference (80,000-0 = 80,000 ft). This gives an average pressure of 4.30 psia. Now, if a ΔP of +2 is maintained at all times, the average pressure at which the ballast gas enters the fuel tanks during climb or descent becomes $P_{avg} = 6.30$ psia.

^mFor JP-7.

Level flight at 80,000 ft. corresponds to a tank pressure of $(0.4 + 2.0) = 2.4$ psia. The mean flight pressure, P_{MF} , can now be calculated,

$$P_{MF} = \frac{(512 + 3,843) \times 6.3 + 2,100 \times 2.4}{512 + 3,843 + 2,100}$$

$$P_{MF} = 5.03 \text{ psia}$$

The molar volume of gas (V_1) is determined for the conditions at which the ballast gas is delivered to the fuel tank:

$$t_1 = 200^\circ\text{F} \quad \therefore \quad T_1 = 660^\circ\text{R}$$

$$P_{MF} = 5.03 \text{ psia} = P_1$$

assuming ideal gas behavior. Thus,

$$V_1 = \frac{14.7}{492} \times 359 \times \frac{660}{5.03}$$

$$V_1 = 1,407 \text{ ft}^3/\text{lb-mole}$$

The total amount of water to be removed during the flight is:

6980 ft ³ air	0.21 moles O ₂	mole	1 mole H ₂ O	18 lb H ₂ O
	mole air	1,407 ft ³	1.4 moles O ₂	lb-mole

$$13.4 \text{ lb. water per flight}$$

(2) Flight Plan No. 1, 10% Initial Vapor Space

The slight changes in P_{MF} and V_1 compared with the above situation are neglected. Therefore, the only change involves the amount of ballast gas during the climb. In this situation, the cruise flow rate is started after three minutes of ascent.

$$\text{Ascent: } \left[\sum_{n=0}^{n=3} (23-2.15 \int_0^n dn) \right] + (20-3) \times 15 = 335 \text{ cf}$$

$$\text{Cruise: } = 2,100 \text{ cf}$$

$$\text{Descent: } = 3,843 \text{ cf}$$

$$\text{Total Ballast Gas } = 6,278 \text{ cf}$$

$$6,278 \times 1.081 = 6,790 \text{ cf air per flight}$$

Total Combustion Air = 6,790 cf

6,790	0.21	mole	1	18 lb. H ₂ O	= 13.0 lb. water/flight
		1,407 cf	1.4	mole	

13.0 lb. water per flight

(3) Flight Plan No. 2, No Initial Vapor Space

This is Flight Plan No. 2. By reference to Table XII it is seen that the ascent period is exactly the same as in the non-emergency flight, and the cruise period is shortened to 136 minutes (Periods 3 and 4 combined) during which $15 \times 136 = 2,040$ cf of ballast gas is needed. Thus, the ballast gas requirements differ significantly only in the subsequent periods relating to descent.

During the powered dive portion of the emergency descent, the gas flow rate is 3,653 cfm for a period of 0.5 min. During the gradual dive (last 1 min.) portion of this descent, the change in pressure is from 7.747 psia at 17,000 ft. to 14.2 psia at 1,000 ft. altitude. Thus, ΔP is 6.453 psi/min. and the flow rate due to pressure change is

$0.9 \times 30,000 \text{ gal}$	6.453	atm.	ft^3	$= 1,585 \text{ cfm}$
	min	14.7 psi	7.48 gal	

Now adding for fuel consumption: $1585 + 43 = 1,628 \text{ cfm}$. Finally, during the approach for landing (0.5 min. duration):

$0.9 \times 30,000$	$14.7-14.2 \text{ psi}$	atm.	ft^3	$+ 3 = 249 \text{ cfm}$
	0.5 min.	14.7 psi	7.48 gal	

Thus, the total volume of gas required during an emergency descent is:

$$\begin{aligned}
 \text{powered dive portion} &= 0.5 \times 3,653 &= 1,827 \text{ cf} \\
 \text{gradual dive portion} &&= 1,628 \\
 \text{approach for landing} &= 0.5 \times 249 &= 125 \\
 \text{Total} &= 3,580 \text{ cf}
 \end{aligned}$$

The average pressures are:

$$\begin{aligned}
 \text{Altitude from 0 to 1,000 ft} & 14.35 \text{ psia} \\
 \text{Altitude from 1,000 to 17,000 ft} & 10.65 \\
 \text{Altitude from 17,000 to 80,000 ft} & 2.53
 \end{aligned}$$

The mean fuel tank pressure for the entire flight is calculated:

$$\begin{aligned}
 512 \times (4.30 + 2) &= 3,226 \text{ psia-cf} \\
 2,040 \times (0.40 + 2) &= 4,896 \text{ " } \\
 1,827 \times (2.53 + 2) &= 8,276 \text{ " } \\
 1,628 \times (10.65 + 2) &= 20,594 \text{ " } \\
 125 \times (14.35 + 2) &= 2,044 \text{ " } \\
 \hline
 6,132 \text{ cf} &= 39,036 \text{ psia-cf}
 \end{aligned}$$

$$P_{MF} = \frac{39,036}{6,132} = 6.4 \text{ psia}$$

The mean molar volume is

$$V_2 = \frac{14.7}{492} \times 359 \times \frac{660}{6.4}$$

$$V_2 = 1,112 \text{ ft}^3/\text{lb-mole}$$

Now the water requirement is determined:

Ascent	512 cf
Cruise: 136 x 15	2,040
Descent	<u>3,580</u>
Total Ballast Gas =	6,132 cf

Total air = $6,132 \times 1.081 = 6,630$ cf

Total Combustion Air = 6,630 cf

The amount of water formed is:

6,630 cf air	0.21	mole	1	18 lb. H ₂ O
		1,112 cf	1.4	mole

16.1 lb. water per flight

(4) Flight Plan No. 2, 10% Initial Vapor Space

Again, neglecting the slight changes in P_{MP} and V_2 , the only change is during climb, where 335 cf of ballast gas are required, for a total of 5,955 cf, or $5,955 \times 1.0811 = 6,438$ cf of air.

The amount of water to remove is

6,438	0.21	1	18
	1,112	1.4	

15.6 lb. water per flight

g. Rate of Water Formation and Removal

It is essential for design purposes to determine the rates of water formation during various periods of a flight. The following calculations were made for the ballast gas flow rates of interest. As developed in Section V-6-1 below, a part of the combustion water (55%) will be removed by condensation in a heat exchanger (HE #3) immediately upstream from the gas dryer. Therefore, the drier duty will equal 45% of the water formed. The calculation model for the rate of water removal in the dryer is:

Air flow rate, cfm	0.21	mole	1	18 lb. H ₂ O	0.453
		molar volume, cf	1.4	mole	

and the values of interest are tabulated:

Ballast Gas Demand, cmf	Corresponding Air Flow Rate, cfm	Pressure in Fuel Tank ^a , psia	Molar Volume, cf	Rate of Water Formation #/Min.	Rate of Water Removal in Gas Drier #/Min.
15	16.2	2.4	2,950	0.015	0.007
363	392	15.54	456	2.33	1.05
3,653	3,949	4.53	1,563	6.82	3.09
1,628	1,760	12.65	560	8.49	3.84

^aAverage pressure for the appropriate altitude range.

h. Quantity of Catalyst

The method of calculation for the quantity of catalyst required was outlined in Section V-3-c. Base values already developed for the SST in parts 6a-6g of this Section were used in making the following calculations. These include the assumptions that a 10% excess of fuel will be used, and that the equivalent composition and weight of the fuel are C₉H₂₀ and 128, respectively.

By these means, the values shown in Table XIII were computed for each of the ballast gas flow rates of concern for the SST.

Two oxygen conversion levels, 96% and 75%, were used in calculating the volume of catalyst, V_c. The specific weight of catalyst A (40.6 lbs./cu. ft.) was assumed in the last stages of the calculation, and the results for the situations of interest are presented in Table XIV. As indicated in the table, 96% conversion during a normal descent was chosen as the basis for conceptual design of a catalytic combustor under Flight Plan No. 1, and 75% conversion during the gradual dive portion of an emergency descent (covering the altitude change from 17,000 to 1,000 feet elevation) was chosen for Flight Plan No. 2. Other combinations might be selected, among which there are two shown in Table XIV that require larger amounts of catalyst. However, these would provide 96% oxygen conversion under high-demand conditions, and seem unwarranted because those chosen will satisfy the target performance.

1. Flight Plan No. 1 - Average Flows and Conditions

The flows of heat and materials, and the conditions affecting performance of the subsystem, are influenced significantly by the specific flight plan. Immediately following is the development of balances for Flight Plan No. 1, representing the average conditions for such items as tank pressure, compressor air temperature, and cooling water temperature. Results are entered on the flow diagram which appears in Figure 36 and shows all of the pertinent streams and items of equipment.

TABLE XIII. CALCULATION OF FACTORS DETERMINING QUANTITY OF CATALYST FOR EST

EO Demand (at 800°) cfm	V ₁ Air Flow at 800° (1.0611 x EO) cfm	P ₁ Ave. Press. in Fuel Tank psia	V ₁ x P ₁ cfm-psia	V ₂ Air Flow at Est. Conditions (0.0548856 x P ₁) cfm	Air Molar Rate of Air (V ₂ x 388.55) moles/min.	M _{O₂} Molar Rate of O ₂ (M _{air} x 0.21) moles/min.	P/O ₂ Feed Rate of O ₂ (M _{O₂} x 60) moles/hr.	M _{fuel} Molar Rate Fuel (M _{air} x 0.0165) moles/min.	W _{fuel} Weight Rate Fuel lbs/min.	Fuel Vapor Rate (W _{fuel} x 2.55) cfm	W _T Total Flow (V ₂ + V ₁) cfm	Initial O ₂ Conc. (W _{O₂} ÷ W _T) lb-moles/cu. ft.
15	16.2	2.4	39	2.14	0.0055	0.0016	0.07	0.0009	0.016	0.03	2.17	0.000533
53	32	15.54	6,100	335	0.86	0.181	10.85	0.0142	1.819	4.64	339	0.000533
3,653	3,950	4.53	17,900	982	2.53	0.531	31.84	0.0417	5.337	13.61	996	0.000533
1,668	1,760	12.65	22,300	1,222	3.15	0.660	39.63	0.0519	6.642	16.94	1,239	0.000533
249	269	16.35	4,400	242	0.62	0.131	7.83	0.0103	1.313	3.35	245	0.000533

TABLE XIV. WEIGHT AND VOLUME OF CATALYST FOR SST

Flight Situation	Dry BG cfm	F _{AO} Oxygen Feed Rate, lb-moles/hr.	Conversion = 96%			Conversion = 75%		
			V _c , ft ³	W _c , lb.	SV, hr ⁻¹	V _c , ft ³	W _c , lb.	SV, hr ⁻¹
Cruise, level flight	15	0.07	0.0023	0.1	58,000	0.001	0.04	137,000
Normal descent	363(a)	10.85	0.351(a)	14.3(a)	58,000(a)	0.149	6.03	137,000
Emergency descent, power dive	3,653	31.84	1.031	41.9	58,000	0.436	17.7	137,000
Emergency descent, gradual dive	1,628(b)	39.63(b)	1.203	52.1	58,000	0.542(b)	22.01(b)	137,000(b)
Emergency descent, landing	249	7.83	0.253	10.3	58,000	0.108	4.4	137,000

(a) Used as basis for combustor design Flight Plan No. 1. Compressor air available at 21.5 psia (ave of entire descent) or 67.7 psia during period of maximum change.

(b) Used as basis for combustor design Flight Plan No. 2. Compressor air available at 38 psia (80,000 to 17,000 feet) and 160 psia (17,000 to 1,000 feet).



FIGURE 36. HEAT AND MASS BALANCE: AVERAGE CONDITIONS FOR SST FLIGHT PLAN NO. 1.

(1) Data

- (a) Heat of absorption (ΔH_{ra}) of water (including the heat of condensation in the amount of 1,050 BTU/# water):

for CaCl_2 = 1,500 BTU/lb. water absorbed

for CaSO_4 = 1,700 BTU/lb. water absorbed

- (b) Heat of vaporization of fuel,

= 106 BTU/# at boiling point
100 BTU/# at 600°F.

- (c) Heat of reaction for JP-7 = 18,750 BTU/#

- (d) Average boiling point for JP-7 = 426°F.

- (e) Density JP-7: at 60°F = 6.66 lb/gal (0.7981 g/ml)
at 300°F = 5.848 lb/gal
at 325°F = 5.765 lb/gal
at 600°F = 4.91 lb/gal

- (f) Average heat capacity (specific heat) of fuel:

between 325 and 600°F C_p = 0.6925 BTU/(lb)(°F)

between 425 and 600°F C_p = 0.720 "

- (g) Molecular weight of air = 28.9

- (h) Average heat capacity of air:

between 225 and 932°F C_p = 0.2526 BTU/(lb)(°F)

between 225 and 1,112°F C_p = 0.2549 "

between 600 and 1,200°F C_p = 0.2606 "

- (i) "Compensation Factor" converts requirements of dry ballast gas into those of air (because of water formation and removal):

1.081 (see Section V-3)

- (j) Each 1.4 moles of oxygen (O_2) will produce 1 mole of water (H_2O).

- (k) All heat content data are based on 32°F as the reference point.

(2) Assumptions

- (a) Volume of ballast gas to be delivered to fuel tank = 1,000 ft³/min.
- (b) Pressure of ballast gas leaving drier and entering the fuel tank = 5.03 psia, the mean flight pressure for Flight Plan No. 1 (see Section No. V-6-f).
- (c) Temperature of dry ballast gas leaving drier and entering fuel tank = 200°F.
- (d) Temperature of saturated ballast gas entering the drier = 100°F.
- (e) Cooling water temperature:
 - at start of flight = 40°F
 - at end of flight = 80°F
 - average for flight = 65°F
- (f) Fuel available, as cooling medium, at 300°F.
- (g) Fuel flow rates (to engines):
 - cruise = 107 gpm (at 60°F) = 712 #/min.
 - idle = 107 ÷ 5 = 21 gpm (at 60°F) = 140 #/min.
- (h) Equivalent composition of JP-7 is C₉H₂₀, thus its molecular weight is 128.
- (i) 10% excess (over stoichiometric) fuel is used in the reactor.
- (j) Temperatures of available air (high-pressure tap)
 - near idle = 250°F
 - cruise = 800°F
 - power dive = 1,000-1,300°F
 - average for normal flight = 600°F
- (k) Preheated air leaves reactor jacket at
 - 600°C = 1,112°F
- (l) Moist ballast gas leaves the reactor catalyst bed at or below the hot spot temperature of 725°C = 1,337°F.

- (m) Complete oxygen conversion is assumed for the purpose of calculating: heat of combustion, water formation, water removal and flows.
- (n) Moist ballast gas leaves HE No. 2 at 340°F, the fuel at 350°F.
- (o) Cooling water leaves HE No. 3 at 210°F.
- (p) Cooling water leaves gas drier at 180°F, co-current flow pattern.
- (q) Fuel vapor pressure in the fuel tank is neglected. (This makes our calculations more conservative.)
- (r) Zero water content is assumed for the compressed air supplied by the engines.

(3) Heat and Material Balances

Appendix E summarizes the calculations involved in developing the heat and material balances for the SST average flight conditions, using the above data and assumptions. Most of the results are shown on the flow diagram in Figure 36. Following is a tabulation of the important values.

• Molar volume at assumed conditions	1,407 ft ³ /lb-mole	
• Air flow for 1,000 cfm ballast gas	1,081 ft ³ /min.	
	22.21 lb/min.	
• Fuel flow to combustor	1.623 lb/min.	
• Mixture flow to combustor	23.82	"
• Rate of water formation	2.075	"
• Water condensed in HE #3	1.135	"
• Water removed in gas drier	0.94	"
• Dry ballast gas delivery	21.75	"
• Total cooling water requirement	27	"
• Fuel required as coolant	114	"

It may be remarked that the total cooling water required for the drier and HE #3 is in excess of that required for the combustor, and wet steam will issue from the combustor cooling coils.

(4) Flight Requirements

The above results, in conjunction with the total combustion air flow during a flight, can be used to calculate the total flight requirements. For example, it is recalled that the total air requirement for Flight Plan No. 1 (with no initial vapor space in the fuel tanks) is 6,980 ft³.

(a) Total cooling water consumption:

$$\frac{6,980 \times 27}{1,000 \times 1.081} = 175 \text{ lbs.}$$

(b) Total water removed by condensation:

$$\frac{6,980 \times 1.135}{1,000 \times 1.081} = 7.34 \text{ lbs.}$$

(c) Total water removed in drier:

$$\frac{6,980 \times 0.94}{1,000 \times 1.081} = 6.07 \text{ lbs.}$$

The sum of (b) and (c) above equals the total amount of water formed in the combustion reaction, because 100% removal is assumed.

j. Flight Plan No. 1- Design Flows and Conditions

In the following presentation, design flows and conditions are generated for that part of Flight Plan No. 1 that represents maximum ballast gas demand. This is the period of normal descent, when the rate of ambient and fuel tank pressure increase equals 1.4 psi/minute. As previously determined:

Dry ballast gas demand = 363 cfm

Dry ballast gas temperature = 200°F

Pressure in fuel tank = 15.54 psia

The flows and conditions were calculated as in the previous situation, but only the bases and results are shown.

(1) Data

The data are the same as in the previous calculations for average conditions.

(2) Assumptions

Only those that differ from the ones listed in the calculations for average conditions are indicated below.

- Cooling water available at 80°F.
- Fuel flow rate (near idle) = 21 gpm (at 60°F) 140 #/min.
- Air available from high pressure tap at 250°F.
- The remaining (unused) fuel vapor present in the gas that leaves the reactor is considered as ballast gas (that is nitrogen and CO₂) with regard to its thermal and flow behavior.

(3) Results

Most are indicated in the flow diagram given in Figure 37. Following is a tabulation of the important values.

- Molar volume at assumed conditions = 455.5 ft³/lb-mole.
- Air flow to supply 363 cfm of dry ballast gas = 392.4 cfm
= 24.9 lb/min.
- Fuel flow to combustor = 1.82 lb/min.
- Mixture flow to combustor = 26.72 #/min.
- Rate of water formation = 2.33 #/min.
- Water condensed in HE #3 = 1.27 #/min.
- Water removal in gas drier = 1.05 #/min.
- Dry ballast gas delivery = 24.39 #/min.
- Total cooling water requirement = 34.8 #/min.
- Fuel required as coolant = 52 #/min.

Again, the total rate of cooling water needed for HE 3 and the gas drier is excessive for the reactor.

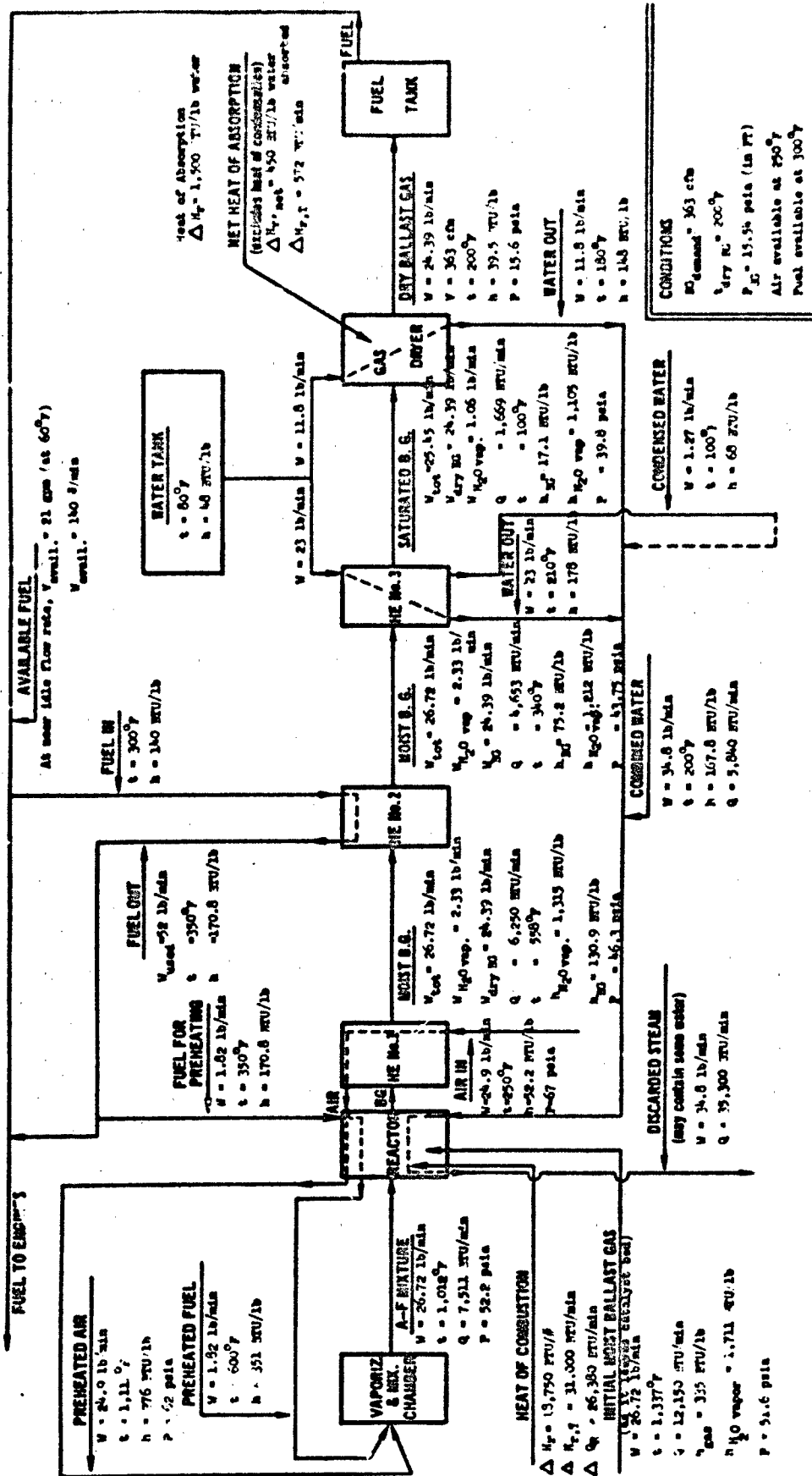


FIGURE 17. HEAT AND MASS BALANCE: DESIGN CONDITIONS FOR SST FLIGHT PLAN NO. 1

k. Equipment Design, Flight Plan No. 1

The foregoing permit sizing and design of the components of the inerting subsystem. Design of the combustor is based on peak demand for ballast gas, which occurs during the descent period. Design of the gas drier must satisfy two criteria: ability to handle the peak demand, and capacity to hold (without regeneration) the total quantity of water to be absorbed over a minimum number of flight hours. The total system must be capable of functioning during the period of critical pressure drop (high-altitude level flight).

(1) Results

Details of the design and weight calculations are given in Appendix F. The results obtained are summarized below, with all figures rounded to the nearest pound:

(a) Air and Fuel Feed Equipment

Supply piping	19 lbs.
Spray nozzle assembly	1
Vaporization chamber	91
Chamber outlet piping	14
Heater	<u>12</u>
Sub-Total	137 lbs.

(b) Combustor

Core tubes	5 lbs.
Catalyst retention screens	73
Catalyst	14
Catalyst diluent	116
Cooling tubes	323
Outer wall	135
Outlet section	11
Fuel preheat tubing	5
Heating elements	<u>12</u>
Sub-Total	694 lbs.

(c) Heat Exchanger HE 1

Duct	322 lbs
Cooling tubes	<u>1426</u>
Sub-Total	1748 lbs

(d) Heat Exchanger HE 2

Duct	48 lbs.
Cooling tubes	<u>109</u>
Sub-Total	157 lbs.

(e) Heat Exchanger HE 3

Duct	78 lbs.
Cooling tubes	<u>127</u>
Sub-Total	205 lbs.

(f) Drier

Outer wall	154 lbs.
Cooling tubes	237
Desiccants	989
Filter and Screens	13
Water tank and water	<u>306</u>
Sub-Total	1699 lbs.

(g) Total Subsystem

<u>Component</u>	<u>Pounds</u>	<u>%</u>
Drier	1699	37
HE-1	1748	38
Combustor	694	15
HE 3	205	4
HE 2	157	3
Feed Streams	137	3
TOTAL	<u>4640</u>	<u>100</u>

(2) Discussion of Weight and Size

The largest and heaviest item in the combustor feed equipment is the vaporization and mixing chamber, which is 5'-3" long and weighs 91 pounds. It is designed for use with a two-fluid nozzle. Design conditions are 1100°F and 220 psig, the maximum pressure expected from the high-stage compressors. The savings in weight that would possibly result from use of alternate types of equipment were not evaluated. The weight of the electrical startup heater is minor (12 pounds).

The combustor is a major item, measuring 43" long by 21" in diameter, and weighing 694 pounds. Nearly half of this weight is for the cooling tubes embedded in the catalyst, and the next heaviest subitems are 135 pounds for the outer wall and 116 pounds for diluent. Possibilities for weight savings exist in several areas: use of an alloy for the finned tubes having better strength-weight properties than 316 SS; full optimization of the diameter and length of the combustor, and dimensions and spacing of tubes and fins; and detailed comparisons of other combustor types with the radial type.

The heat exchanger (HE 1) which preheats the combustion air and provides the first substantial cooling of the combustion gases is the heaviest of the components. It is housed in a duct measuring 2 feet x 2 feet x 5.3 feet long. The 23 banks of finned tubes (0.93" ID) weigh 1,426 pounds, and the duct itself weighs 322 pounds. These weights are based on the use of Hastelloy C, and the flow of the cooler fluid (air) in the space external to the tubes, which favors a thinner duct wall. Other alloys were not considered, and dimensions have not been optimized.

The next two heat exchangers are housed in a duct measuring 1 foot x 1 foot x 5.3 feet long. The fuel-cooled portion is of 316 SS construction, while the larger, water-cooled section is made of aluminum. The weight of the duct walls is 126 pounds, and the combined weight of fuel and water tubing is 236 pounds. Here again, the design has not been optimized for minimum weight.

The drier is the second-heaviest component. The combination of CaCl_2 with zeolite yields a residual water concentration of 10 ppm (volume) at 150°F and an overall average design space velocity of 380 hr^{-1} . Weight and efficiency are better than can be achieved with the CaCl_2 - CaSO_4 combination. Temperature is the dominant factor governing the performance vs weight relationship. It was found that substantial benefits in both performance and weight can be achieved by increasing the quantity of cooling water in order to reduce the drier temperature from 200°F (original plan, see Figure 37) to 150°F. This is illustrated by the following summary of calculations made for the combination, CaCl_2 plus CaSO_4 .

Exit gas temperature, °F	150	200
Exit water conc., ppm	100	1,000
Total bed volume, ft ³	30.4	83.5
Total weight of agents, lb	2,053	5,430
Cooling water per flight, lb	122	55

Dramatically, the 67 pounds of additional cooling water reduces the exit water concentration by an order of magnitude, and effects a saving of more than 3300 pounds in weight of agent alone. This is accomplished by maintaining a constant temperature difference of 20°F between gas and coolant throughout the length of the drier, using parallel flow.

This departure from the scheme presented in Figure 37 does not affect any components other than the drier, since during most of the flight the ballast gas is likely to reach a temperature of 200°F (from contact with the hot walls) soon after entering the fuel tanks.

The drier is 1 foot x 2 feet x 12.8 feet long, exclusive of the transition pieces at each end. It is charged with a combined total of 989 pounds of CaCl₂ and zeolite, and provides protection over a period of 50 flight hours without regeneration.

A tank of cooling water is included as a part of the drying equipment; its weight including initial water supply is 300 pounds. The other main weight items are the finned aluminum cooling coils, weighing 237 pounds, and the aluminum outer wall, weighing 154 pounds. Here again the dimensions and spacing have not been optimized.

The total subsystem weight of 4,640 pounds does not include the weight of the controls, some connecting lines, structural supports, and insulation. It represents 2.3% of the initial fuel load (200,000 pounds).

1. Flight Plan No. 2 - Average Flows and Conditions

Calculations of average flow rates and conditions of temperature and pressure are made in a similar way to those presented above for Flight Plan No. 1. Details are omitted; only the important assumptions and results are given below. Note that all flows are related to 1,000 cfm of ballast gas, and that 100% conversion of oxygen is assumed.

(1) Conditions and Assumptions

BG demand	1,000 cfm
BG temperature (in FT)	200°F
Pressure in FT	6.37 psia
Oxygen conversion	100%
Avg cooling water inlet temperature	60°F ^a
Drier cooling water exit temperature	180°F
Fuel: temperature	300°F
cruise flow rate	712 lb/min
Avg temperature of air entering subsystem (at HE 1)	975°F

All other assumptions remain as in FP No. 1 unless calculations dictate otherwise.

(2) Results

Molar volume at average conditions	1,111 ft ³ /lb-mole
Amount of air required for 1,000 cfm BG	1,081 cfm
Weight of air	28.11 lb/min
Weight of fuel required	2.05 lb/min
Weight of air-fuel mixture	30.17 lb/min
Weight of water formed (100% conversion)	2.63 lb/min

^a Shorter flight time means less heat into water than in FP No. 1.

Amount of water removed by condensation	1.44 lb/min
Amount of water removed in drier (100% efficiency)	1.19 lb/min
Weight of dry BG delivered to FT	27.5 lb/min
Combined cooling water for HE 3 and drier	30.1 ^m lb/min
Amount of fuel required as coolant	247 lb/min

For a complete flight, including 10% excess for any contingency, the load of cooling water for the inerting subsystem is 205 lb.

The heat and mass balances for the various components in the subsystem during SST Flight Plan No. 2 (average conditions are presented in Figure 38.

(3) Use of Additional Cooling Water

Under FP No. 1, it was found that the temperature of the BG leaving the drier can be reduced to 150°F by using an additional quantity of cooling water. Similar calculations for FP No. 2 show that the same can be accomplished with the following flows and conditions:

drier cooling water exit temp.	130°F
cooling water rate (drier)	22.3 lb/min
cooling water rate (drier + HE 3)	42.1 ^m lb/min
total cooling water per flight, incl. 10% excess	285 lb

m. Flight Plan No. 2 - Design Flows and Conditions

Design flows and conditions are based on the peak flow rate expected during the powered dive, namely 1628 cfm. As in the preceding subsection, BG temperature is 200°F, but a lower conversion level of 75% is employed.

(1) Conditions and Assumptions

BG demand	1,628 cfm
BG temperature	200°F
Pressure in FT	12.65 psia
Conversion	75%

^mNearly sufficient for the combustor, which needs 30.3 lb/min. Balance to be achieved by collecting and using the condensate from HE 3.

^mMore than sufficient to supply the combustor.

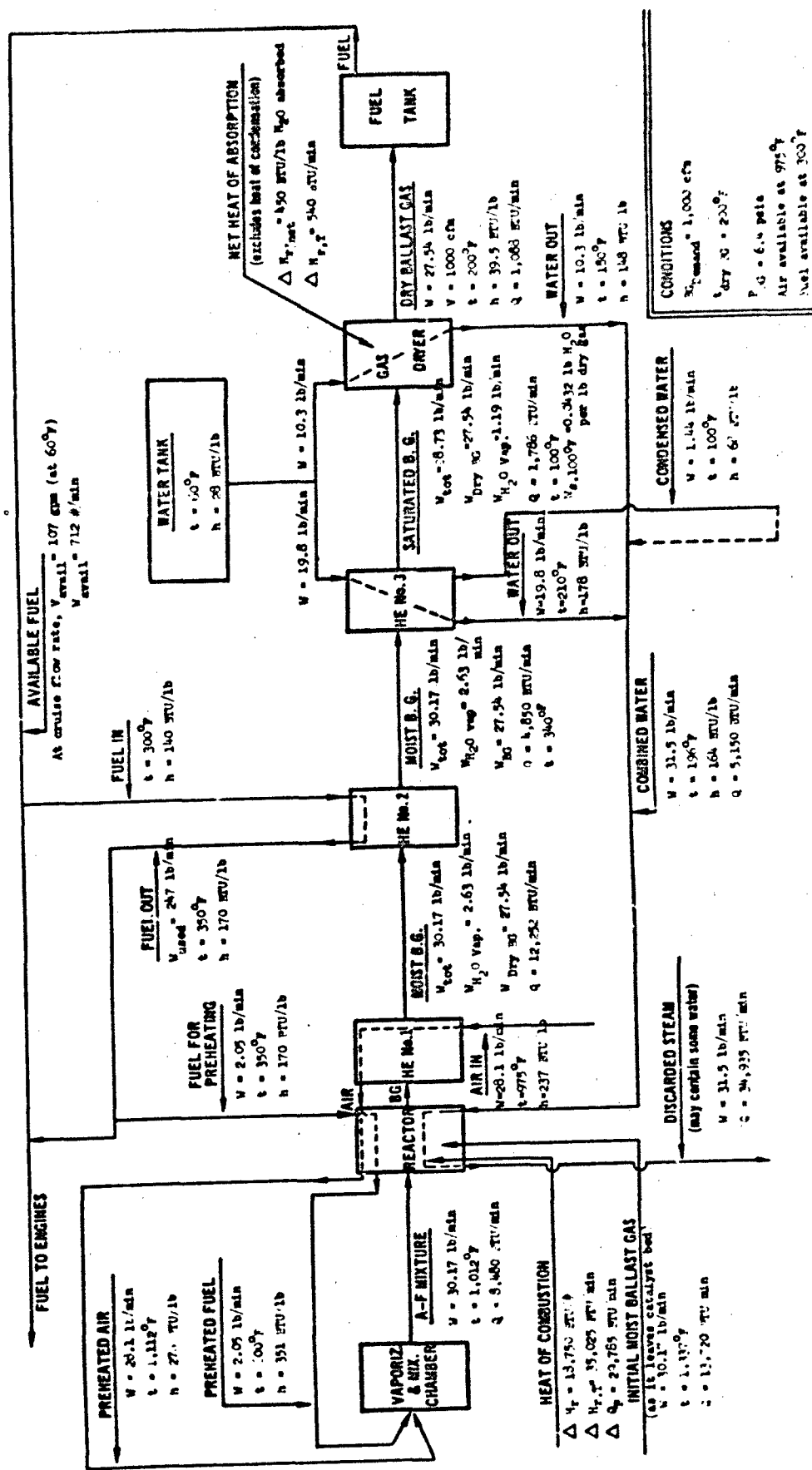


FIGURE 38. HEAT AND MASS BALANCE: AVERAGE CONDITIONS FOR SST FLIGHT PLAN NO. 2

Cooling water inlet temperature	75°F
Drier cooling water exit temperature	180°F
Fuel: temperature	300°F
full power flow rate	2,140 lb/min
Temperature of air entering subsystem	1,200°F
All other assumptions remain unchanged.	

(2) Results

Molar volume at design conditions	560 ft ³ /lb-mole
Amount of air required for 1,628 cfm BG	1,760 cfm
Weight of air	90.9 lb/min
Weight of reaction fuel required	6.64 lb/min
Weight of air-fuel mixture	97.5 lb/min
Weight of water formed (75% conversion)	6.37 lb/min
Amount of water removed by condensation	2.52 lb/min
Amount of water removed in drier	3.85 lb/min
Amount of fuel removed by condensation	2 lb/min
Weight of dry BG delivered to FT	89.2 lb/min
Combined requirements for cooling water	105 lb/min
Amount of fuel required as coolant	822 lb/min

A chart showing the flows and conditions throughout the subsystem is given in Figure 39.

(3) Use of Additional Cooling Water

The temperature of the BG leaving the drier can be reduced to 150°F by using additional cooling water, as in the previous case. In this instance, the combined cooling water requirement (HE 3 plus drier) reaches 158.5 lb/min versus 105 lb/min needed in the combustor.

n. Equipment Design, Flight Plan No. 2

(1) Method

The equipment design generated for the SST inerting subsystem under Flight Plan No. 1 was used as a point of departure for Flight Plan No. 2. The latter calls for a larger subsystem, and the weight of each

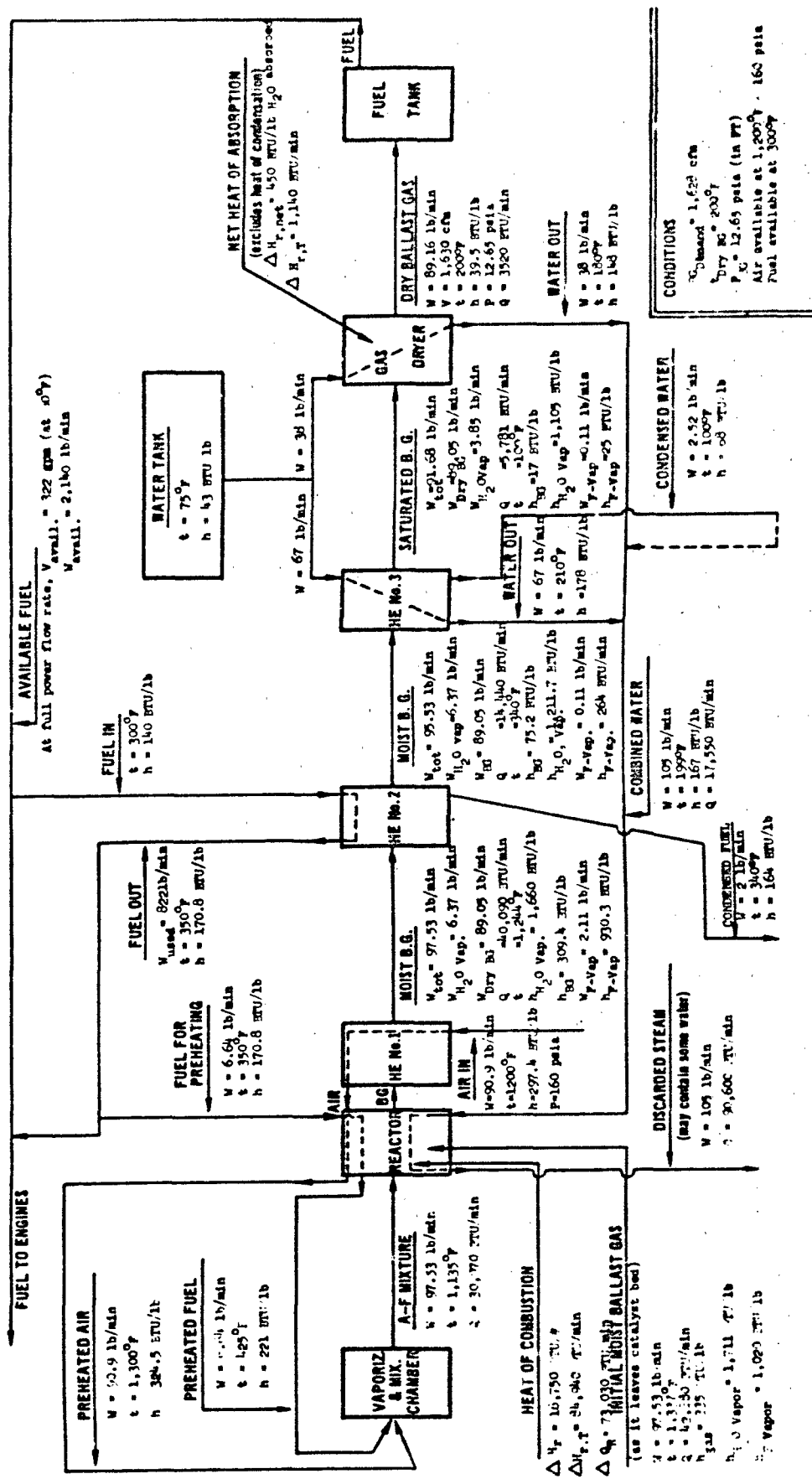


FIGURE 39. HEAT AND MASS BALANCE: DESIGN CONDITIONS FOR SST FLIGHT PLAN NO. 2

component was scaled up by an appropriate method, as described in Appendix G where the calculations are presented.

Special attention was given to a weight comparison between two combustor designs. The radial design was scaled up from SST FP No. 1, and compared against the segmented design.

The design was not checked for pressure drop.

(2) Results

The following summary of weights is taken from the calculations in Appendix G.

(a) Air and Fuel Feed

supply and outlet piping	100 lb
spray nozzle	1
vaporization chamber	202
heater	24
fuel booster pump	10

Sub Total 337 lb

(b) Combustor (Radial)

entire unit, by scale factors	1,444 lb
-------------------------------	----------

(c) Combustor (Segmented)

retention screens (8)	54 lb
catalyst	24
catalyst diluent	---
cooling tubes	352
outer wall (duct), baffles	170
fuel preheat tubing	17
heating elements	13

Sub Total 630 lb

(d) Heat Exchanger HE 1

Same as FP No. 1 1,748 lb

(e) Heat Exchanger HE 2

Entire unit, by scale factors 239

(f) Heat Exchanger HE 3

Entire unit, by scale factors 225 lb

(g) Drier

outer wall (duct)	577 lb
cooling tubes	431
desiccants	3,667
gas filter and screens	40
water tank, water, pump	335
Sub Total	5,050 lb

(h) Total Subsystem (with Segmented Reactor)

<u>Component</u>	<u>Pounds</u>	<u>%</u>
Drier	5,050	61
HE 1	1,748	21
Combustor	630	8
Feed Streams	337	4
HE 2	239	3
HE 3	225	3
	<u>8,229</u>	<u>100</u>

(3) Discussion of Weights

The drier weight dominates the subsystem, representing 61% of the entire package. In comparison to the drier for FP No. 1, it is heavier by a factor of 3 and handles 3.7 times the volume of BG. This dominant position of the drier is mainly a result of weight savings achieved for the other major components.

The weight of HE 1 is only 21% of the package in this instance. No change in weight (vs FP No. 1) is required because the air is supplied to the subsystem at a much higher temperature, and only requires 100°F of preheat. The segmented combustor weighs less than half as much as the scaled radial type, and its weight is only 8% of the subsystem weight.

As in the previous case, the subsystem weight does include the weight of a cooling water tank and pump, plus the water required for the inerting subsystem. It does not include the weight of controls, structural supports, insulation, and some connecting lines.

7. CASE ANALYSIS II - TACTICAL AIRCRAFT

a. Basis

A hypothetical tactical mission representing present-day ground support operations was obtained through the cooperation of the Air Force Aero Propulsion Laboratory. The mission profile is shown in Figure 40, where several significant differences from Case I can be noted. The altitude does not exceed 35,000 feet, there are two refuelings, and there are four descent periods during which ballast gas required for pressure adjustments in the fuel tanks adds to the water absorption capacity required in the drier. Total flight time is 155 minutes, of which 38 minutes are spent at full power and 30 minutes at idle. The remainder is classed as cruise power. A tabulation of pertinent descriptors for the flight is given in Table XV.

b. Fuel Flow Rates

$$\text{Tank capacity} = 2,000 \text{ gal} = 267.4 \text{ ft}^3$$

$$90\% \text{ full capacity} = 1,800 \text{ gal} = 241 \text{ ft}^3$$

Assume two drop tanks, capacity 300 gal. each

$$\text{Total fuel per mission} = 2,000 (0.75^{\text{M}} + 0.75^{\text{M}} + 0.80) + 600 = 5,200 \text{ gal}$$

$$\text{Cruise fuel rate} = R_c$$

$$\text{Maximum fuel rate} = R_m = 3 R_c$$

$$\text{Idle fuel rate} = R_I = 0.2 R_c$$

Maximum fuel rate applies for 25% of flight

Idle fuel rate applies for 19.5% of flight

$$155 \text{ min} (0.25 R_m + 0.195 R_I + 0.555 R_c) = 5,200 \text{ gal}$$

$$0.25 \times 3 R_c + 0.195 \times 0.2 R_c + 0.555 R_c = (5,200 \div 155) \text{ gal/min}$$

$$0.75 R_c + 0.039 R_c + 0.555 R_c = 33.55 \text{ gpm}$$

$$1.344 R_c = 33.55 \text{ gpm}$$

$$R_c = 25 \text{ gpm}$$

$$= 3.34 \text{ cfm}$$

$$= 160 \text{ lb/min}$$

*Each refueling = (90-20%) + 5% for fuel consumed while refueling.

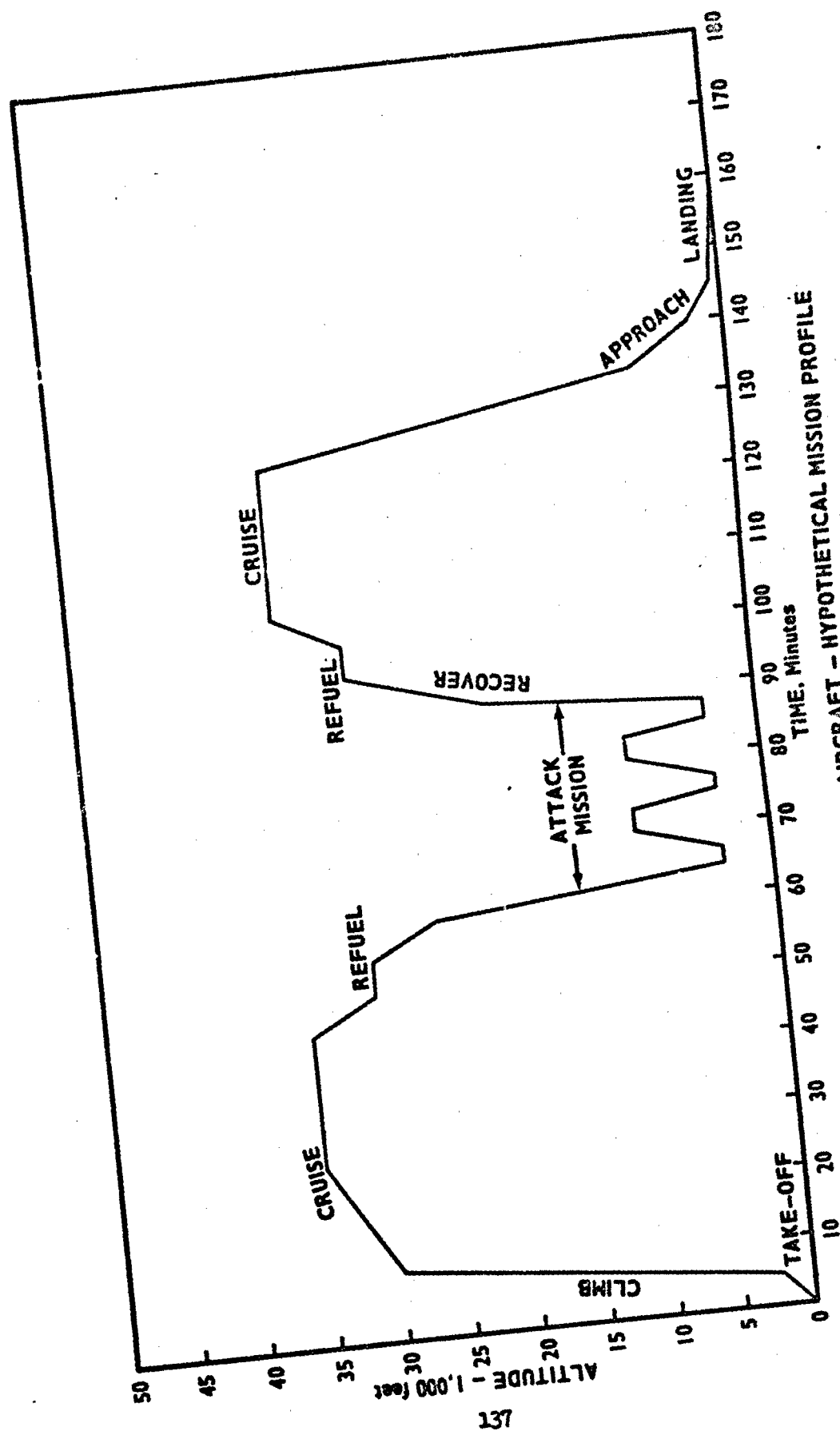


FIGURE 40. TACTICAL AIRCRAFT - HYPOTHETICAL MISSION PROFILE FOR GROUND SUPPORT MISSION

TABLE XV. TACTICAL AIRCRAFT: MISSION PLAN

No.	Time, Min. Period Duration	Operation	Altitude ft	Altitude Change ft	Rate of Altitude Change ft/min.	Amount of Fuel, % Fuel Capacity
1	0-5 5 ^m	Take-off	0-2 M	2,000	400	90
2	5-10 5 ^m	Climb	2-30M	28,000	5,600	
3	10-25 15	Cruise altitude approach	30-35M	5,000	333	
4	25-40 20	Level flight	35M	0	0	
5	45-50 5	Descent to refuel altitude	[35-30M]	[-5,000]	[-1,000]	20
6	50-55 5	Refueling	30M	0	0	
7	55-60 5 ^m	Approach to attar	[30-25M]	[-5,000]	[-1,000]	90
8	60-64 4 ^m	Attack dive	[25-3.4M]	[-21,600]	[-5,400]	80
9	64-67 3	Attack	3.4M	0	0	
10	67-70 3 ^m	Climb	3.4-10M	6,600	2,200	70
11	70-73 3 ^m	Approach to attack	10M	0	0	
12	73-75 2 ^m	Attack dive	[10-3.4M]	[-6,600]	[-3,300]	60
13	75-77 2	Attack	3.4M	0	0	
14	77-80 3 ^m	Climb	3.4-10M	6,600	2,200	50
15	80-83 3 ^m	Approach to attack	10M	0	0	

Full power

(table continued)

TABLE XV. TACTICAL AIRCRAFT: MISSION PLAN (continued)

No.	Time, Min. Period	Duration	Operation	Altitude ft	Altitude Change ft	Rate of Altitude Change ft/min	Amount of Fuel, % Fuel Capacity
16	83-85	2 ^M	Attack dive	[10→3.4M]	[-6,600]	[-3,300]	40
17	85-87	2	Attack	3.4M	0	0	
18	87-90	3 ^M	Recover (climb)	3.4→20M	16,600	5,540	30-35
19	90-95	5	Refuel altitude approach	20→30M	16,000	2,000	20
20	95-100	5	Refuel	30M	0	0	
21	100-105	5	Cruise altitude approach	30→35M	5,000	1,000	90
22	105-125	20	Cruise	35M	0	0	
23	125-134	9(a)	Descent	[35→7M]	[-28,000]	[-3,110]	30
24	134-140	6(a)	Approach to land	[7→2.5M]	[-4,500]	[-750]	25
25	140-145	5(a)	Approach to land	[2.5→0.9M]	[-1,600]	[-320]	
26	145-150	5(a)	Landing	[0.9→0.3M]	[-600]	[-120]	20
27	150-155	5(a)	Landing	[0.3→0M]	[-300]	[-60]	10

Total Time 155 Min.

Total Time at Full Power 38 Min. (0.25 total time)

Total Time at Idle 30 Min. (0.195 total time)

Full Power

(a) Idle

$$\begin{aligned}
 R_m &= 75 \text{ gpm} \\
 &= 10.03 \text{ cfm} \\
 &= 479 \text{ lb/min} \\
 R_I &= 5 \text{ gpm} \\
 &= 0.67 \text{ cfm} \\
 &= 32 \text{ lb/min}
 \end{aligned}$$

Because of the low fuel rate at idle condition, it may be necessary to circulate fuel through HE 2 during the descent and approach to landing, in order to provide sufficient cooling capacity. The temperature of the fuel available for cooling is assumed to vary during the mission as shown in Figure 41, which is based on information furnished by the Air Force Aero Propulsion Laboratory. A design temperature of 60°F is chosen because the design situation represents the descent, when temperatures are expected to be at this level or lower.

c. Ballast Gas Demand

(1) Total Requirements

Total requirements were obtained by summation of the demand during each element of the flight, calculated by the same or similar methods used in Case I for the SST, neglecting the fuel and volume of the drop tanks.

Initial climb (10% vapor space)	40 cf
Cruise	117
Refueling descent (80% vapor space)	67
Refueling	17
Approach to combat zone (10% vapor space)	56
Initial attack dive (20% vapor space)	89
3 attack passes (level flights)	24
2 attack approaches (level flights)	60
Climb after first attack (30% vapor space)	10
Second attack dive (40% vapor space)	48 cf

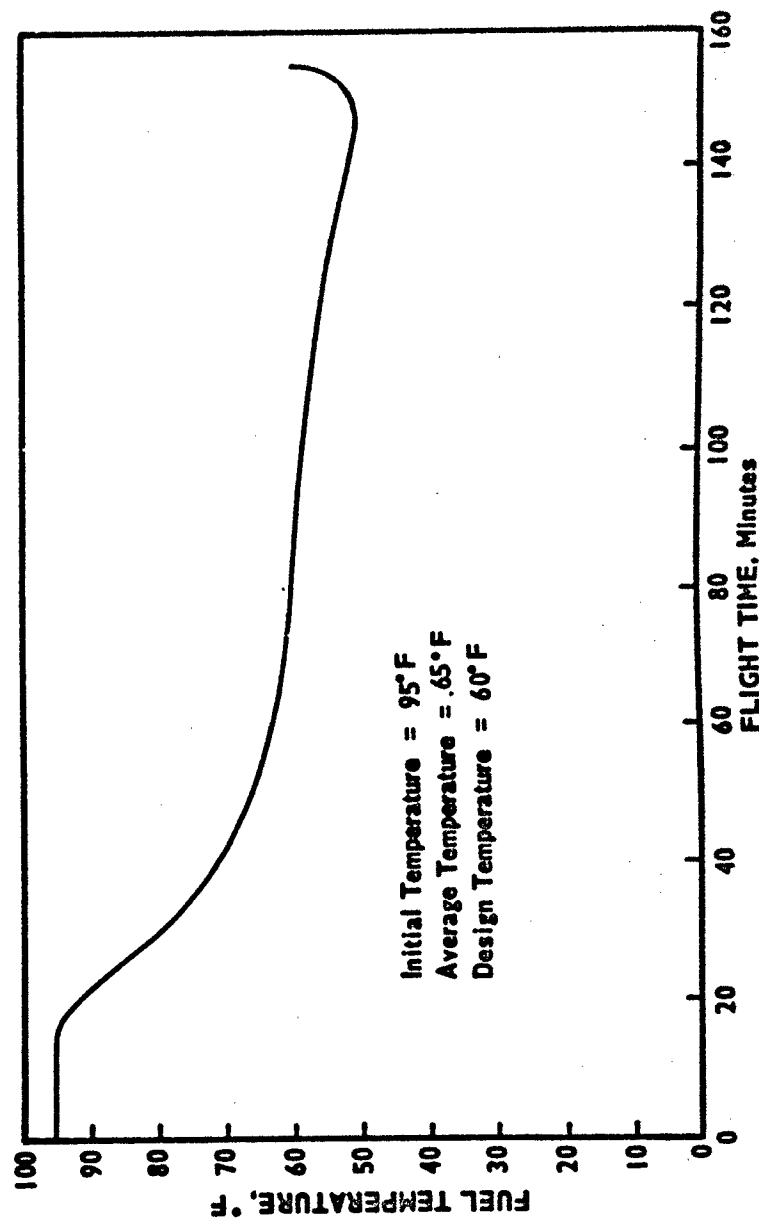


FIGURE 41. TACTICAL AIRCRAFT - FUEL TEMPERATURE PROFILE

Climb after second attack (50% vapor space)	10 cf
Third attack dive (60% vapor space)	62
Recovery climb (65-70% vapor space)	27
Refueling	17
Approach to cruise altitude (10% vapor space)	39
Cruise	67
Descent (70% vapor space)	263
Approach to landing (75% vapor space)	40
Landing (80% vapor space)	49 cf
<hr/>	
TOTAL PER FLIGHT	1,102 cf

The above total is based on use of the cruise flow rate as a minimum flow rate during the climbs, as was done in the case of the SST.

(2) Design Rate

Maximum demand occurs during the third attack dive, when 60% of fuel tank capacity is occupied by vapor, the engines are operating at full power, and a pressure change rate of 14.7 psi/min is experienced. In this situation the ballast gas demand (and flow rate) is:

$$\frac{0.6 \times 2,000 \text{ gal}}{\text{min}} \times \frac{14.7 \text{ psi}}{14.7 \text{ psi}} \times \frac{\text{atm}}{7.48 \text{ gal}} \times \frac{\text{ft}^3}{\text{cfm}} + 10 = \underline{\underline{171 \text{ cfm}}}$$

Design flow rate = 171 cfm

d. Mean Flight Pressure

The average pressures for the altitude ranges corresponding to individual elements of the flight are listed below. These pressures, as well as the mean flight pressure are determined following the same method as outlined for the SST. The pressure in the fuel tank is assumed to be 1 psi above the ambient static pressure.

<u>Altitude Range or Level</u>	<u>Avg. ASP, psia</u>	<u>Avg. Tank Pressure, psia</u>
0 to 30,000 ft	8.71	9.71
30,000-35,000 ft	3.9	4.9
35,000 ft	3.46	4.46
30,000 ft	4.36	5.36
25,000-30,000 ft	4.9	5.9
3,400-25,000 ft	8.86	9.86
3,400 ft	13.06	14.06
3,400-10,000 ft	11.62	12.62
10,000 ft	10.1	11.1
3,400-30,000 ft	8.13	9.13
7,000-35,000 ft	6.78	7.78
2,500-7,000 ft	12.41	13.41
0-2,500 ft	14.09	15.09

Mean flight pressure calculation:

$$40 \times 9.71 = 388.44 \text{ psia-cf}$$

$$50 \times 4.9 \left. \vphantom{\begin{matrix} 50 \\ 67 \end{matrix}} \right\} 117 = 245$$

$$67 \times 4.46 \left. \vphantom{\begin{matrix} 50 \\ 67 \end{matrix}} \right\} 117 = 298.82$$

$$67 \times 4.9 = 328.3$$

$$17 \times 5.36 = 91.12$$

$$56 \times 5.9 = 330.4$$

$$89 \times 9.86 = 877.72$$

$$24 \times 14.06 = 337.44$$

$$60 \times 11.1 = 666$$

$$10 \times 12.62 = 126.2$$

$$48 \times 12.62 = 605.76$$

$$10 \times 12.62 = 126.2$$

$$62 \times 12.62 = 782.44$$

$$\begin{array}{rcl}
 27 \times 9.13 & = & 246.46 \\
 17 \times 5.36 & = & 91.12 \\
 39 \times 4.9 & = & 191.1 \\
 67 \times 4.46 & = & 298.82 \\
 263 \times 7.78 & = & 2,045.61 \\
 40 \times 13.41 & = & 536.48 \\
 49 \times 15.09 & = & 739.17 \\
 \hline
 & = & 9,352.6 \text{ psia-cf}
 \end{array}$$

$$\begin{aligned}
 \text{Mean flight pressure} &= \frac{9,352.6 \text{ psia-cf}}{1,102 \text{ cf}} \\
 &= 8.5 \text{ psia (in fuel tank)}
 \end{aligned}$$

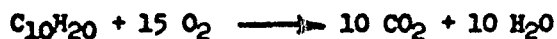
Mean flight pressure = 8.5 psia

e. Water Formation and Removal

(1) Formation

The fuel used is JP-4, whose equivalent composition is $C_{10}H_{20}$ with a molecular weight of 140.

Stoichiometric equation (at 100% conversion)



The molar ratio of oxygen to water is

$$\frac{O_2}{H_2O} = \frac{15}{10} = 1.5$$

and the mass ratio is

$$\frac{O_2}{H_2O} = \frac{15 \times 32}{10 \times 18} = 2.67$$

Stoichiometric equation using air (at 100% conversion)



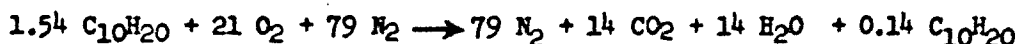
Relations: 1.4 moles fuel to 100 moles air

100 moles air to 107 moles moist BG

100 moles air to 93 moles dry BG

Consequently, removal of water causes a net shrinkage of 7 moles.
To compensate, we need $100 \div 93 = 1.075$ moles (or cf) air for each mole
(or cf) of BG to be supplied.

10% excess fuel and 100% conversion of oxygen

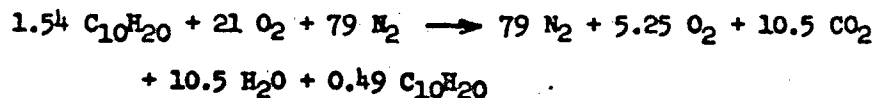


Relations: 1.54 moles fuel to 100 moles air

100 moles air to 107.14 moles moist BG

100 moles air to 93.14 moles dry BG

10% excess fuel and 75% conversion



Relations: 1.54 moles fuel to 100 moles air

100 moles air to 105.74 moles moist BG

100 moles air to 94.77 moles dry BG

(2) Total Water to be Removed

To be conservative water removal is based on 100% conversion, although actually during portions of flight (especially dives) the conversion level will be considerably lower.

Because the temperatures of the fuel and of the cooling water are much lower than in the SST case, it may be assumed that the dry BG will reach the fuel tank at the following conditions:

$$T = 560^\circ\text{R}$$

$$P = 8.5 \text{ psia}$$

The molar volume of gas is

$$V_m = \frac{14.7}{492} \times 359 \times \frac{560}{8.5} = 706.7 \text{ ft}^3/\text{lb-mole}$$

The total amount of air necessary to supply the required amount of BG is

$$1,102 \times 1.075 = 1,185 \text{ cf air per flight.}$$

The total amount of water formed and to be removed is

1,185 cf air	0.21%	mole	1	18 lb H ₂ O
	O ₂	706.7	1.5	mole

4.23 lb water per flight

As is shown later, 2.86 lb are removed by condensation and 1.37 lb in the gas drier.

f. Amount of Catalyst

This calculation is made by the method used for the SST in Case I. Following is a summary of calculations.

V_{BG} (at 100°F and 12.62 psia), cfm	171
$V_1 = V_{AIR} = 1.075 V_{BG}$, cfm	184
P_1 = pressure in fuel tank, psia	12.6
$V_1 \times P_1$	2,320
$V_2 = V_1 P_1 [532.5/(560 \times 14.7)]$, cfm	150
V_m = molar volume (at 72.5°F and 14.7 psia), cf/lb-mole	388
$N_{AIR} = V_2 \div V_m$ lb-moles air/min	0.386
$N_{O_2} = 0.21 N_{AIR}$ lb-moles oxygen/min	0.0811
$F_{AO} = 60 N_{O_2}$ lb-moles oxygen/hr	4.87
$N_f = 0.0154 N_{AIR}$ lb-moles fuel/min	0.00595
$W_f = 146 N_f$ lb fuel/min	0.833
Specific volume of fuel vapor, ft ³ /lb	3.04
$V_f = W_f \times \text{Sp. vol.}$, cfm	2.53

^aFor JP-4.

$V_T = V_2 + V_F$, cfm	152
$C_{AO} = N_{O_2} \div V_T$, moles/ft ³	0.00053
k (assumed the same as for JP-7)	194,000
$k C_{AO}$	103.45
$F_{AO}/k C_{AO}$	0.0470

Conversion, %	96	75
E_A	0.0552	0.0414
$\left[(1 + E_A) \ln \left(\frac{1}{1-X_A} \right) - E_A X_A \right]_0^{X_A}$	3.34	1.41
V_C , ft ³ (see equation (A), part V-3-c)	0.157	0.066
$W_C = \rho_C V_C$, lb	6.4	2.7

g. Material and Heat Balance for Average Conditions

(1) Bases

BG demand = 100 cfm
 BG temperature = 100°F
 Pressure in fuel tank = 8.5 psia

(2) Data

- Heat of reaction for JP-4 = 18,500 BTU/lb
- Average boiling point of JP-4 = 336°F
- Density of JP-4: at 60°F = 6.381 lb/gal
 at 100°F = 6.237 "
 at 200°F = 5.877 "
 at 300°F = 5.522 "
- Heat of vaporization of JP-4 = 110 BTU/lb (estimated)
- Conversion factor = 1.075 (to convert BG demand into air requirement)
- Each 1.5 moles oxygen will produce 1 mole water
- Curves were developed for thermodynamic properties of liquid and vapor JP-4.

(3) Assumptions

Items of equipment and streams of materials referred to below are displayed in Figure 42.

1. Temperature of dry BG entering fuel tank = 100°F
2. Temperature of saturated BG leaving HE 2 = 85°F.
(Contrary to Case I, there is no need for HE 3.)
3. Moist BG leaves catalyst bed at or slightly below 1,337°F
4. At all times during the flight, cooling water is available at a temperature of 40°F. [In fact, it may be inferred from the fuel temperature profile (Figure 41) that occasional heating will be necessary to prevent freezing.]
5. The cooling water leaves the gas drier at ~80°F.
6. Fuel is available as coolant at 65°F, and leaves HE 2 at 150°F. Its maximum temperature at any time during the flight is 200°F.
7. Fuel flow rate = cruise flow rate = 25 gpm (at 60°F) = 160 lb/min.
8. Equivalent composition of JP-4 is $C_{10}H_{20}$, with molecular weight of 140.
9. 10% excess fuel (over stoichiometric requirements) is used in the combustor.
10. Reaction fuel is preheated to 300°F. Higher temperatures are avoided to prevent fouling as a result of thermal degradation.
11. Air is available from high pressure tap at 600°F.
12. Air is preheated in HE 1 to 1,112°F.

(4) Results

Calculations made as per the methods used in Case I yielded the results given in Figure 42. Following is a tabulation of the important values.

Molar volume at average conditions	706.7 ft ³ /lb-mole
Flow of air for 100 cfm BG	107.5 cfm
Weight of air	4.4 lb/min
Amount of fuel required	0.328 lb/min

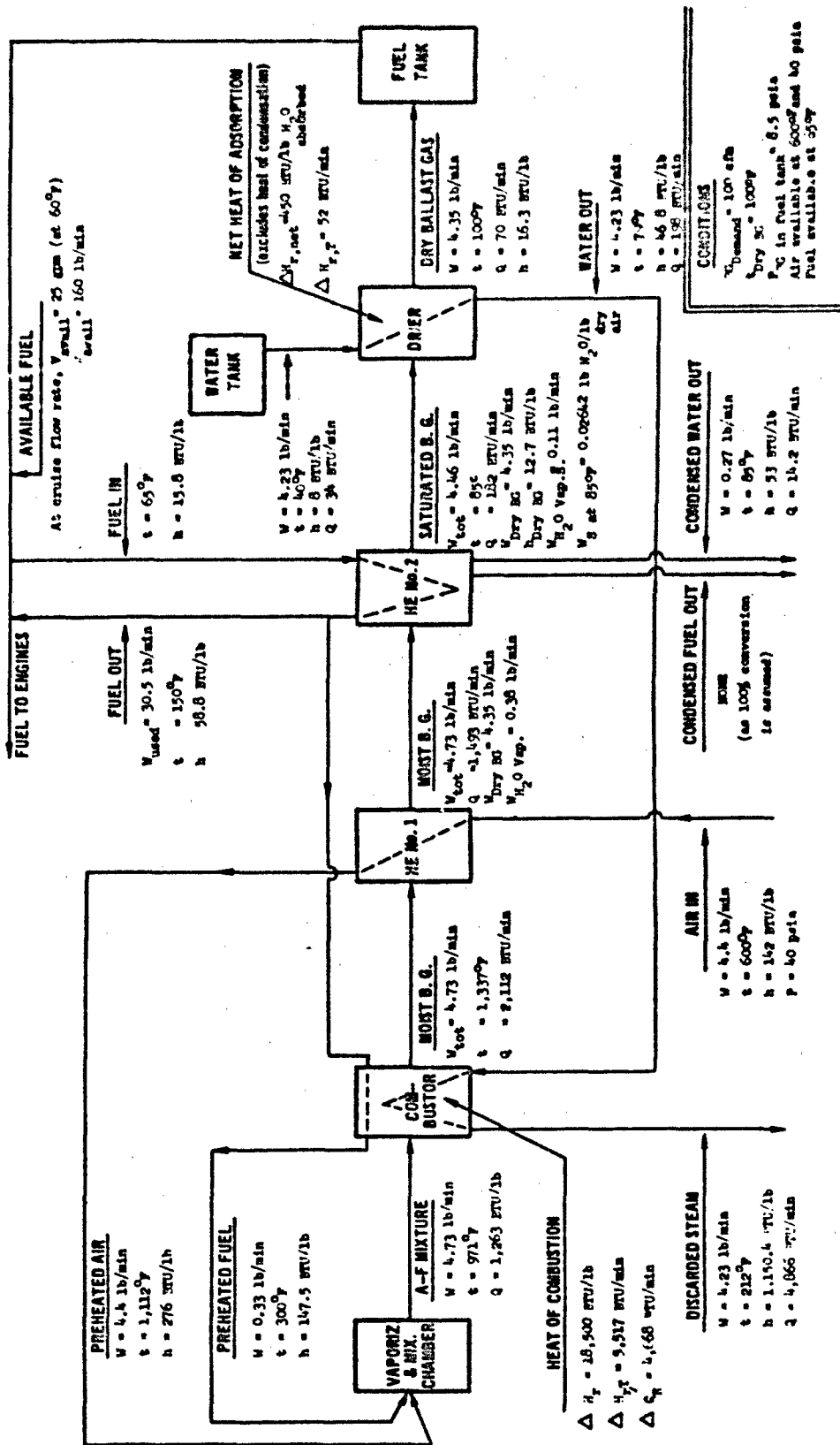


FIGURE 42. HEAT AND MASS BALANCE: AVERAGE CONDITIONS FOR TACTICAL AIRCRAFT

Weight of air-fuel mixture	4.73 lb/min
Amount of water formed	0.383 lb/min
Quantity of water removed by condensation	0.268 lb/min
Quantity of water removed in gas drier	0.115 lb/min
Amount of dry ballast gas delivered to FT	4.34 lb/min
Amount of cooling water required	4.23 lb/min
Amount of fuel necessary as coolant	30.5 lb/min

These values are on the basis of 100 cfm of ballast gas. Totals for the entire flight are obtained by multiplying the above results by $1,102 \div 100 = 11.02$.

The total amount of cooling water, including 10% extra for contingency, is 52 lb per mission of 155 minutes.

h. Material and Heat Balance for Design Conditions

(1) Bases

BG demand = 171 cfm
 BG temperature = 100°F
 Pressure in FT = 12.62 psia

(2) Data

Same as for Average Conditions

(3) Assumptions

Listed below are the assumptions that differ from those shown for Average Conditions.

1. The amount and temperature of cooling water leaving the drier is calculated in conjunction with the combustor design calculations.
2. Fuel is available for cooling at 60°F
3. Fuel flow at full power is 75 gpm (at 60°F) = 479 lb/min.
4. 10% excess fuel (over stoichiometric) is used in the combustor, and 75% conversion is assumed.
5. Air from the high pressure tap is available at 1,200°F and 232 psia. It leaves HE 1 at 1300°F.

(4) Results

Conditions and flows are set forth in Figure 43. Calculation details are given in Appendix H. Following is a tabulation of the important values:

- Molar volume at assumed conditions in fuel tank = 476 ft³/lb-mole
- Air flow to supply 171 cfm of dry BG = 184 cfm
= 11.2 lb/min
- Fuel flow to combustor = 0.833 lb/min
- Mixture flow to combustor = 12.00 lb/min
- Rate of water formation = 0.73 lb/min
- Water condensed in HE #2 = 0.439 lb/min
- Excess fuel condensed in HE #2 = 0.252 lb/min
- Non-condensable excess fuel = 0.013 lb/min
- Water removed in gas drier = 0.291 lb/min
- Dry ballast gas delivery = 11.02 lb/min
- Cooling water requirement = 8.3 lb/min
- Fuel required as coolant = 95 lb/min

i. Equipment Design, Tactical Aircraft

(1) Basis

For conceptual design purposes, it is assumed that the peak demand for ballast gas, which occurs under "design conditions", represents the peak demand and design condition for each component in the inerting package. This may not actually be true, but a definitive design study of each component is beyond the scope of the present program. As in the SST situation, the drier, which accumulates water as it performs the drying function, must be sized for capacity as well as efficiency of performance.

Table XV indicates that, during most of the flight, air will be available from the high stage of the compressors at a pressure of 40.7 psia, or above. Although design conditions represent a period of powered descent when air is available at a higher pressure, it is assumed that a regulator in the line adjusts the pressure to the stated value.

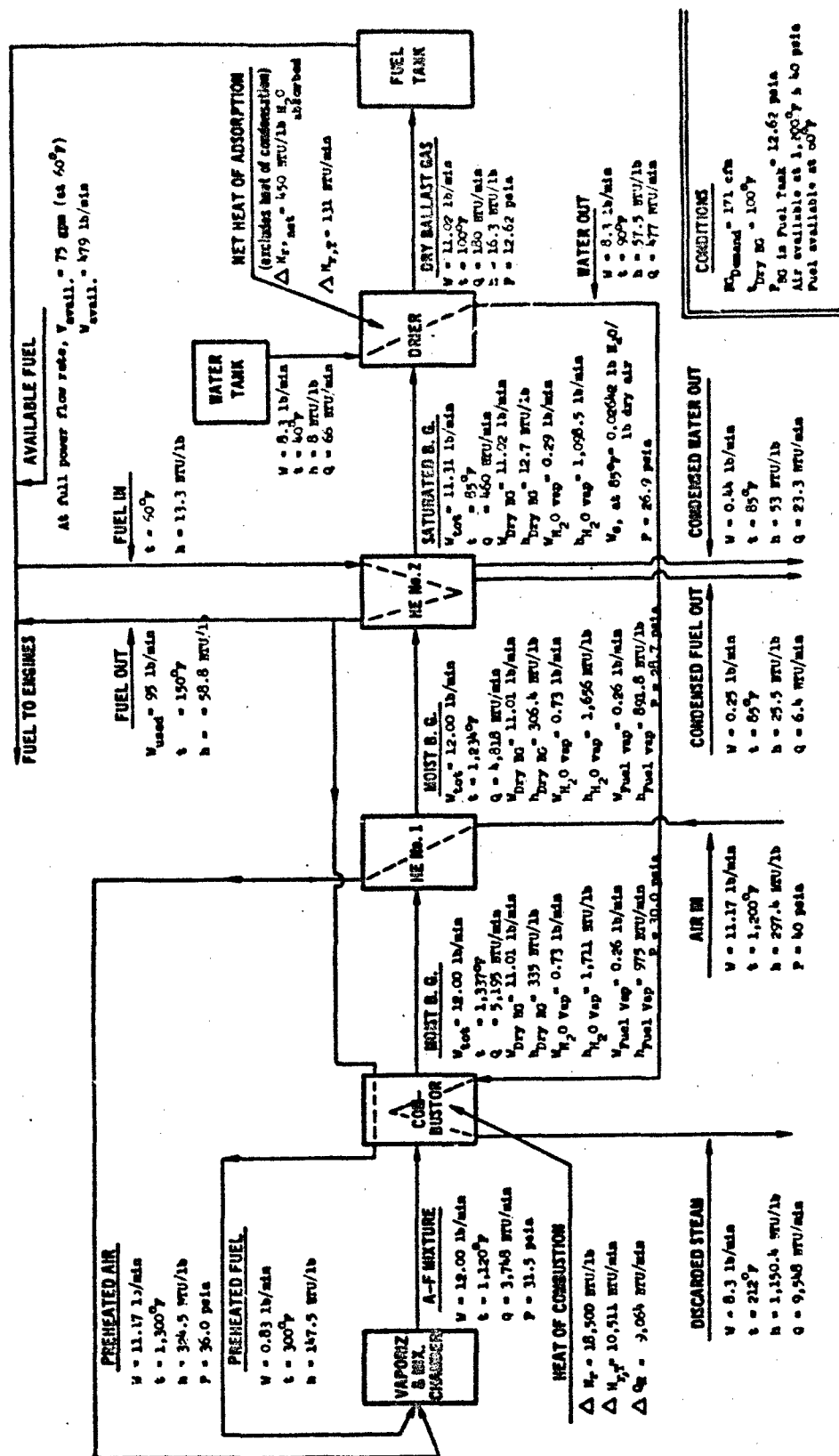


FIGURE 43. HEAT AND MASS BALANCE: DESIGN CONDITIONS FOR TACTICAL AIRCRAFT

The main features of this design are:

- use of a segmented reactor.
- omission of HE 3

With the exception of the vaporization chamber, the major components can be located within a common duct through which the ballast gas passes, always remaining on the duct side of heat exchange tubes. Questions concerning duct size, and changes in duct size from one section to another, are not resolved in this study. The schematic diagram in Figure 44 describes the system in concept. Details of the calculations are given in Appendix H.

(2) Results

The results obtained are summarized below:

(a) Air and Fuel Feed Equipment

Supply piping	11 lb
Spray nozzle assembly	1
Vaporization chamber	27
Chamber outlet piping	13
Heater	3
	<u>55 lb</u>

(b) Combustor

Catalyst	4 lb
Screens (6)	10
Heaters	3
Fuel preheat pipe	2
Cooling tubing	61
Duct (housing)	30
	<u>110 lb</u>

(c) Heat Exchanger HE 1

Duct	61 lb
Cooling tubing	211
	<u>272 lb</u>

(d) Heat Exchanger HE 2

Duct	61 lb
Cooling tubing	191
	<u>252 lb</u>

(e) Drier

Outer wall	39 lb
Cooling tubing	67
Desiccants	194
Filter, screens	5
Water tank and water	70
	<u>375 lb</u>

- 1 VAPORIZATION CHAMBER (VC)
- 2 COMBUSTOR (1' wide x 1' high)
- 3 HE1 (2' x 1' high)
- 4 HE2 (2' x 1' high)
- 5 Drier (1' x 1' high)

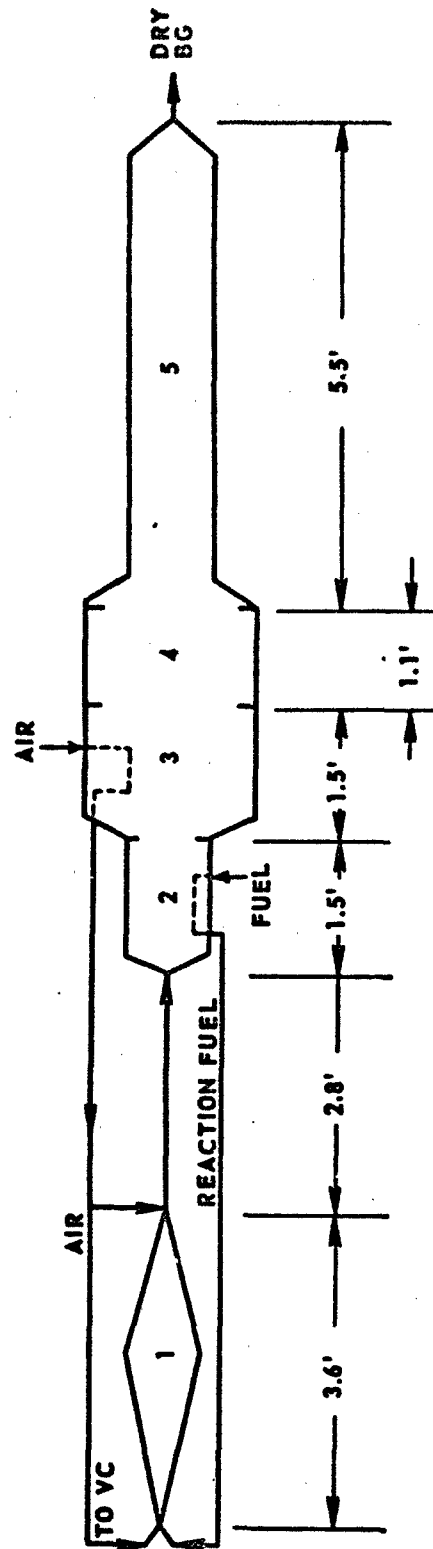


FIGURE 44. DIAGRAM OF THE INERTING SYSTEM FOR TACTICAL AIRCRAFT

(f) Total subsystem

<u>Component</u>	<u>Pounds</u>	<u>%</u>
Drier	375	35
HE 1	272	26
HE 2	252	24
Combustor	110	10
Feed Streams	55	5
	<u>1064</u>	<u>100</u>

(3) Discussion of Weight and Size

The heaviest component is the drier. The combination of CaCl_2 and zeolite is the lowest weight and most efficient combination of the agents considered. However, some further investigation of agents that function best in the lower temperature region (up to 100°F) may yield a saving in size and weight. A detailed design study may also lead to a change in the quantity of desiccants required, which provide a higher-than-target 73 hours of protection in the present design. Overriding any other changes that may result from the above would be changes in design targets, such as an increase in the allowable quantity of moisture in the ballast gas.

The second-heaviest component, HE 1, is subject to a possible reduction in size and weight as a result of detailed studies directed toward optimization of tubing dimensions, spacing, and duct size. Alloys other than Hastelloy C may offer weight advantages.

Similar comments apply to HE 2, which represents 24% of the subsystem weight.

The segmented combustor design has not been optimized, nor do the calculations reflect any credit for heat transfer by the radiation mechanism. Design of the air and fuel feed equipment has not been optimized; however, this equipment together with the combustor represent only 15% of the entire subsystem weight.

The total subsystem weight of 1,064 pounds does not include the weight of controls, insulation, some connecting lines, and structural supports. It represents 6.4% of the initial fuel capacity (including drop tanks). This is far greater than the corresponding figure for the SST because the SST has a much larger initial fuel storage capacity in relation to the rate of fuel consumption.

8. CASE ANALYSIS III - C-141 TRANSPORT AIRCRAFT

a. Basis

Data on typical C-141 flight parameters and the mission profile (Figure 45) were obtained through the cooperation of the Air Force Aero Propulsion Laboratory. All pertinent information was developed based on the above data and is summarized in Tables XVI and XVII. In addition, the following information and constraints are applicable:

- Water in BG entering fuel tank: < 0.001 lb H_2O /lb dry gas (equivalent to $< 1,555$ ppm H_2O V/V)
- Inerting gas may contain $< 8\%$ oxygen
- Time between regenerations = 42 hrs (equivalent to > 6 cycles as per Table XVI)
- Fuel type: JP-4
- Initial fuel load = 150,000 lb \approx 3,143 cu. ft.

b. Fuel and Cooling Water Temperatures

The initial fuel temperature of the C-141 transport is $90^\circ F$, $5^\circ F$ below that of the Tactical Aircraft, Case Analysis II. The change in C-141 fuel temperature with time can be estimated by reference to Figure 41 (Tactical Aircraft), bearing in mind that differences in the cruise speed, flight altitude and type of mission tend to give lower temperatures in the C-141.

The maximum stagnation temperature for the C-141 at 40,000 ft is given by (2)

$$\frac{T_s}{T_A} = 1 + \frac{\gamma - 1}{2} M^2$$

where

T_A = ambient temperature, $^\circ R = (-69) + 460 = 391^\circ R$

γ = specific heat ratio of air = 1.4

M = Mach number = 0.75

This yields

T_s = stagnation temperature, $^\circ R = 435^\circ R$

$\approx -25^\circ F$

This temperature is realistic for the leading edges of various portions of the aircraft. At other positions, the surface temperatures will be less than the maximum stagnation temperature.

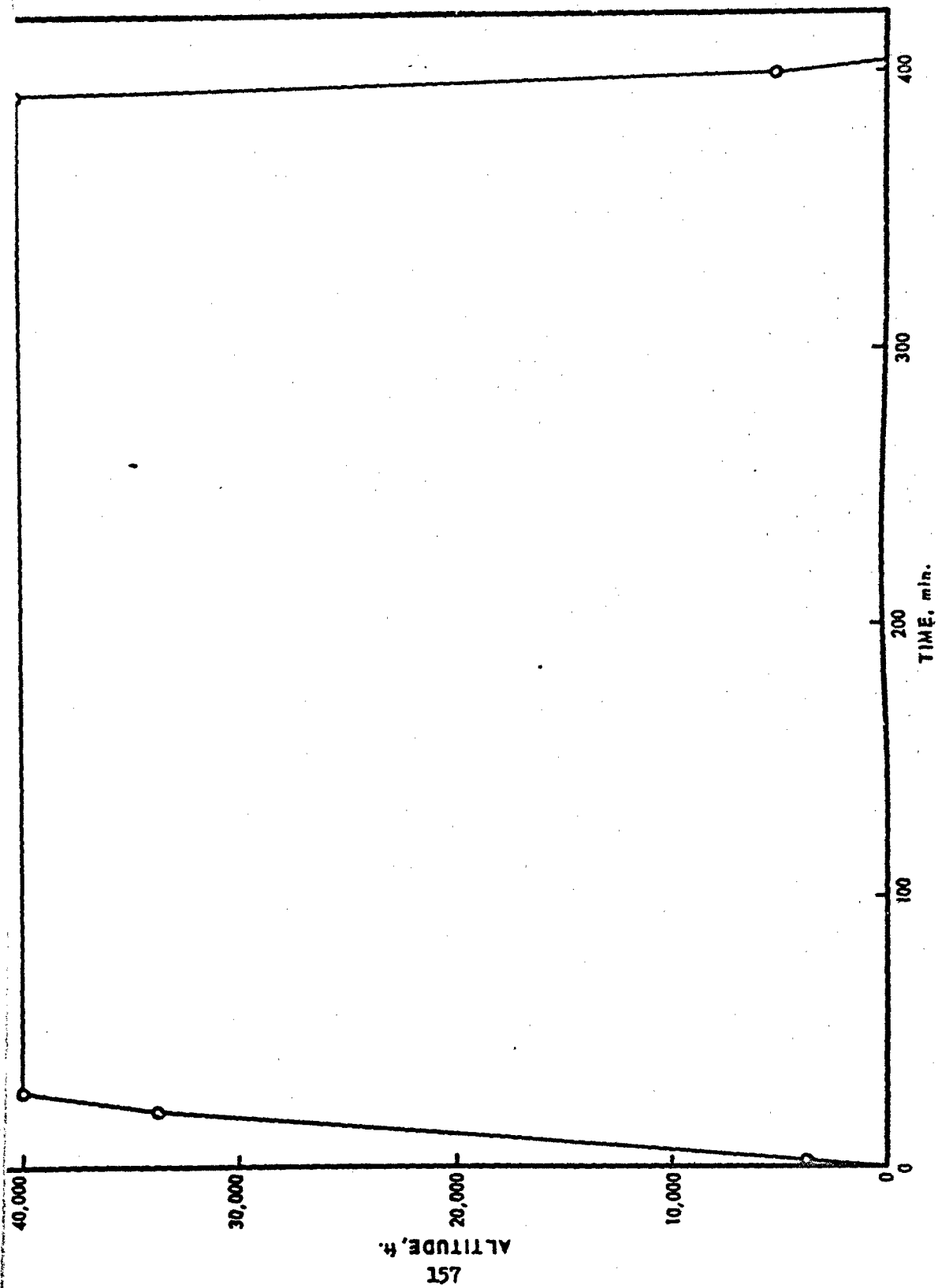


FIGURE 45. FLIGHT PROFILE OF C-141 AIRCRAFT

TABLE XVI: FLIGHT PLAN OF C-141 AIRCRAFT

No.	Operating Period		Description	Ave. Rate of		Altitude, ft	Altitude, ft	Fuel Load % C'py
	Duration, Min.	Cum. Time, Min.		Altitude Change, ft/min	Altitude Change, ft			
1	3	3	Take-off	1,000	3,000	0 → 3M	90	
2	20	23	Climb	1,500	30,000	3 → 33M	---	
3	7	30	Cruise altitude approach	1,000	7,000	33 → 40M	---	
4	363	393	Cruise	0	0	40M	---	
5	6	399	Descent	[-6,000]	[-36,000]	40 → 4M	10	
6	4	403	Approach to Landing	[-1,000]	[-4,000]	4 → 0M	---	

TABLE XVII. FLIGHT DATA FOR C-141 AIRCRAFT

Operation	Engine Bleed Air				Fuel Flow (a)		
	Pressure, psia		Temperature, °F		lb/min	gpm	cfm
	Sea Level	20,000 ft	40,000 ft	Sea Level	20,000 ft	40,000 ft	
Climb	218	132	63	750	660	530	700 110 14.7
Cruise	---	---	55	---	---	500	150 23.5 3.15
Descent	42	26	24	270	230	280	60 9.4 1.26

Cruise Mach No. = 0.75

Fuel tank temperature = 90°F, the temperature at start of flight.

Fuel temperature to engine 120°F

(a) Fuel: JP-4. For volumetric conversions assume fuel at 60°F (5.36 lb/gal).

With regard to mission type and altitude, over 90% of the flight time of the C-141 is spent at 40,000 ft, and there are no dives or other maneuvers.

To be conservative, we will assume that, during most of the flight, the temperature of the fuel in the tank is below 45°F, the average fuel temperature for the entire flight is <50°F, and during descent (design conditions) the fuel temperature is below 40°F. After making allowance for a 30°F rise caused by other cooling duties on the aircraft, we assume that the fuel reaches the inerting system at 75°F on average and at 65°F during the design situation.

Following a similar line of reasoning for the cooling water, it is estimated that

average temperature = 40°F

design temperature = 35°F

based on an initial temperature of approximately 60°F. (It may be necessary to heat this water occasionally to prevent it from freezing.)

c. Ballast Gas Demand

(1) Total Requirements

Climb

A constant BG supply of 14.7 cfm is assumed for the ascent, equivalent to the volumetric rate of fuel consumed by the engines. Thus, the decrease in BG demand due to expansion of gases (because of decrease of ambient static pressure) in the vapor space is disregarded. The above allows removal and venting of oxygen dissolved in the fuel and present in the vapor space.

Consequently, during the 30-minute climb a total of $30 \times 14.7 = 441 \text{ ft}^3$ of BG are required.

Cruise

The cruise lasts 363 min and to replace the fuel 3.15 cfm BG are required. Thus, $363 \times 3.15 = 1,144 \text{ ft}^3$ of BG are necessary.

Descent

It is assumed that at the start of the descent 10% of the original fuel remains in the fuel tank, thus the vapor space is

$$0.9 \times 3,143 = 2,830 \text{ ft}^3$$

The aircraft descends from an altitude of 40,000 ft to sea level with a consequent total pressure change of $14.7 - 2.7 = 12 \text{ psi}$. To compensate for this pressure change and for the fuel used up during the 10-minute descent the amount of BG to supply is:

$$\frac{2,830 \text{ cu. ft.}}{14.7 \text{ psi}} \times \frac{12 \text{ psi}}{14.7 \text{ psi}} + 10 \text{ min} \times 1.26 \text{ cfm} = 2,322 \text{ ft}^3$$

Total BG

For a 403 min flight, the BG demand is:

Climb	441 cf
Cruise	1,144
Descent	2,322
Total	<u>3,907</u>

Total BG per Flight = 3,910 cf

(2) Design Requirements

During the first 6 min, the rate of descent is 6,000 ft/min and the maximum rate of pressure change occurs during the last minute, namely from 10,000 (10.1 psia ASP) to 4,000 ft (12.76 psia ASP). Thus

$$\Delta P/\text{min} = 12.76 - 10.1 = 2.66 \text{ psi/min}$$

The BG demand due to the pressure change and fuel consumption is

$$\frac{2,830 \text{ cu. ft.}}{14.7 \text{ psi}} \times \frac{2.66 \text{ psi}}{14.7 \text{ psi}} + 1.26 = 513 \text{ cfm}$$

Design Flow Rate = 513 cfm

Note: The average design pressure in the fuel tank is

$$\frac{12.76 + 10.1}{2} + 0.5 = \underline{11.93 \text{ psia}}$$

d. Mean Flight Pressure

The mean flight pressure is determined following the same method as outlined for the SST. The pressure in the fuel tank is assumed to be 0.5 psi above the ambient static pressure (ASP).

The average ASP for the altitude range from 0 to 40,000 ft is 7.4 psia, and the ASP at 40,000 ft is 2.71 psia. Thus

$$441 \times 7.4 = 3,263 \text{ cf-psia}$$

$$1,144 \times 2.71 = 3,100$$

$$2,322 \times 7.4 = 17,183$$

$$23,546 \text{ cf-psia}$$

$$\frac{23,546}{3,910} + 0.5 = 6.53 \text{ psia in fuel tank}$$

Mean Flight Pressure = 6.53 psia

e. Water Formation and Removal

(1) Formation

Since use of JF-4 fuel is assumed, the mechanism of water formation described previously in part V-7-e-(1) applies here.

(2) Total Water to Be Removed

The basis and assumptions are the same as in V-7-e-(2), with the exception of pressure, which is 6.53 psia. Thus the molar volume (V_m):

$$V_m = \frac{14.7}{492} \times 359 \times \frac{560}{6.53} = 920 \text{ ft}^3/\text{lb-mole}$$

The total amount of air necessary to supply the required amount of BG is

$$3,910 \times 1.075 = 4,200 \text{ cf air per flight}$$

The total amount of water formed and to be removed is

4,200 cf air	0.21%	mole	1	18 lb H ₂ O	=
	O ₂	920 cf	1.5	mole	

$$11.50 \text{ lb water per flight}$$

As is shown later, 8.05 lb are removed by condensation and 3.45 lb by absorption in the gas drier.

As is shown below in V-8-g-(5), it is appropriate to use 45°F as the temperature of BG delivery to the fuel tank. If V_m is adjusted accordingly, the total amount of water formed and to be removed is 12.75 lb/flight, of which 3.82 lb are removed in the drier and 8.93 are condensed in HE 2.

Water Removal = 12.75 lb per flight

f. Amount of Catalyst

This calculation is made by the method used for the SST. Following is a summary of calculations.

V_{BG} (at 100°F and 11.93 psia), cfm	513
$V_1 = V_{air} = 1.075^{\text{m}} V_{BG}$, cfm	552
P_1 = pressure in fuel tank, psia	11.93
$V_1 \times P_1$	6,580
$V_2 = V_1 P_1 [532.5 / (560 \times 14.7)]$, cfm	426
V_m = molar volume (at 72.5°F and 14.7 psia), cf/lb-mole	388
$N_{air} = V_2 \div V_m$, lb-moles air/min	1.096
$N_{O_2} = 0.21 N_{air}$, lb-moles oxygen/min	0.23
$F_{AO} = 60 N_{O_2}$, lb-moles oxygen/hr	13.81
$N_F = 0.0154^{\text{m}} N_{air}$, lb-moles JP-4/min	0.0169
$W_F = 140^{\text{m}} N_F$, lb JP-4/min	2.36
\bar{V}_F = specific volume of fuel ^m vapor, ft ³ /lb	3.04
$V_F = W_F \times \bar{V}_F$, cfm	7.18
$V_T = V_2 + V_F$, cfm	433
$C_{AO} = N_{O_2} \div V_T$, lb-moles/ft ³	0.00053
k (used the same as for JP-7)	194,000
k C_{AO}	103.1
$F_{AO} / k C_{AO}$	0.134

^mFor JP-4

Conversion, %	96	75
E_A	0.0552	0.0414
$\left[(1 + E_A) \ln \left(\frac{1}{1 - X_A} \right) - E_A X_A \right]_0^{X_A}$	3.34	1.41
V_c , ft ³ (see Equation (A), Part V-3-c)	0.447	0.189
$W_c = \rho_c V_c$, lb	18.2	7.7

g. Material and Heat Balance for Average Conditions

(1) Bases

BG demand = 100 cfm
 BG temperature = 100°F
 Pressure in fuel tank = 6.53 psia

(2) Data

The same data as for the Tactical Aircraft [V-7-g-(2)].

(3) Assumptions

Only those assumptions that differ from the ones used for the Tactical AC [V-7-g-(3)] are listed below.

1. Fuel is available as coolant at 75°F, and leaves HE 2 at 150°F.
2. Flow rate of available fuel = cruise flow rate = 150 lb/min.
3. Engine air is available at 500°F (average temperature per flight; see Appendix I).

(4) Results for BG Temperature of 100°F

Calculations as per methods used in Case I (see Appendix E) yield the results given in Figure 46. Following is a tabulation of the important values, based on 100 cfm of BG:

Molar volume at average conditions	920 cf/lb-mole
Flow of air for 100 cfm BG	107.5 cfm
Weight of air	3.38 lb/min
Amount of fuel required	0.252 lb/min

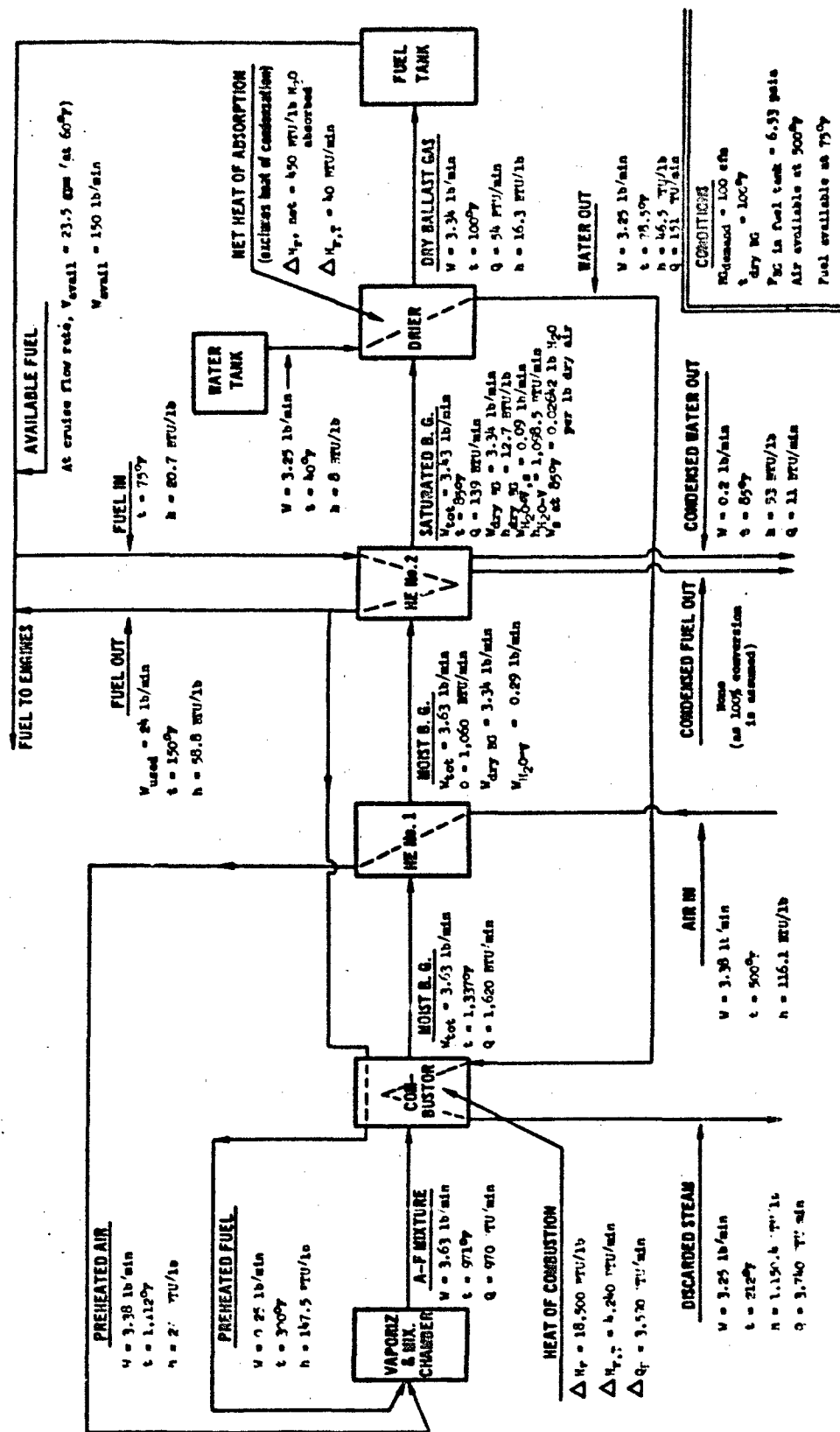


FIGURE 46. HEAT AND MASS BALANCE: AVERAGE CONDITIONS FOR C-141 AIRCRAFT

Weight of air-fuel mixture	3.63 lb/min
Amount of water formed	0.295 lb/min
Quantity of water removed by condensation	0.207 lb/min
Quantity of water removed in gas drier	0.088 lb/min
Amount of dry ballast gas delivered to FT	3.34 lb/min
Amount of cooling water required	3.25 lb/min
Amount of fuel necessary as coolant	24 lb/min

Totals for a 403 min flight are obtained by multiplying the above results by $3,910 \div 100 = 39.1$.

The total amount of cooling water, including 10% extra for contingency, is 140 lb per mission of 403 minutes.

(5) Results for BG Temperature of 45°F

The fuel temperature was assumed to be 50°F on average. Although the inerting subsystem will not be able to deliver the BG at 45°F, the BG will undergo cooling and contraction in the fuel tank. This, in turn, will result in an increase of BG demand, equivalent to BG requirement at 45°F. Consequently, it is conservative to assume that BG is delivered at 45°F. The effect of this temperature on the values of interest is as follows:

Molar volume 829 cf/lb-mole

Weight of air 3.74 lb/min

$$\text{Factor} = \frac{3.74}{3.38} = 1.108$$

Thus, all the results listed in (4) have to be multiplied by 1.108 to obtain the values for BG at 45°F and 6.53 psia, giving for example:

Amount of water formed	0.326 lb/min
Amount of water removed in gas drier	0.098 lb/min
Amount of dry BG delivered to FT	3.70 lb/min
Amount of cooling water required	3.6 lb/min
Total cooling water for 403 min flight	155 lb

The change introduced here affects also the quantity of catalyst to use as follows:

96% conversion	20.2 lb
75% conversion	8.5 lb

h. Material and Heat Balance for Design Conditions

(1) Bases

BG demand = 513 cfm
BG temperature = 100°F
Pressure in FT = 11.93 psia

The gravimetric flow rate of BG is the equivalent to BG delivery at 45°F [as per V-8-g-(5)].

(2) Data

Same as for average conditions.

(3) Assumptions

Listed below are the assumptions that differ from those shown for average conditions or those used for Tactical AC [V-7-h(3)].

1. Fuel available for cooling at 65°F
2. Fuel flow at near idle condition is 60 lb/min.
(To avoid recirculation of hot fuel, during peak demand, fuel may leave HE 2 at or near 300°F, although this is not a desirable situation.)
3. 10% excess fuel (over stoichiometric) is used in the combustor, and 75% conversion is assumed.
4. Air from engine bleed is available at 250°F and 35 psia (see Appendix I).
5. Cooling water is available at 35°F.

(4) Results

Conditions and flows are set forth in Figure 47. Following is a tabulation of the important values:

Molar volume (at 45°F and 11.93 psia)	454 cf/lb-mole
Flow of air for 513.4 cfm BG	552 cfm
Weight of air	35.1 lb/min
Amount of fuel required (combustor)	2.62 lb/min
Weight of air-fuel mixture	37.8 lb/min
Amount of water formed	2.3 lb/min
Quantity of water removed by condensation	1.38 lb/min

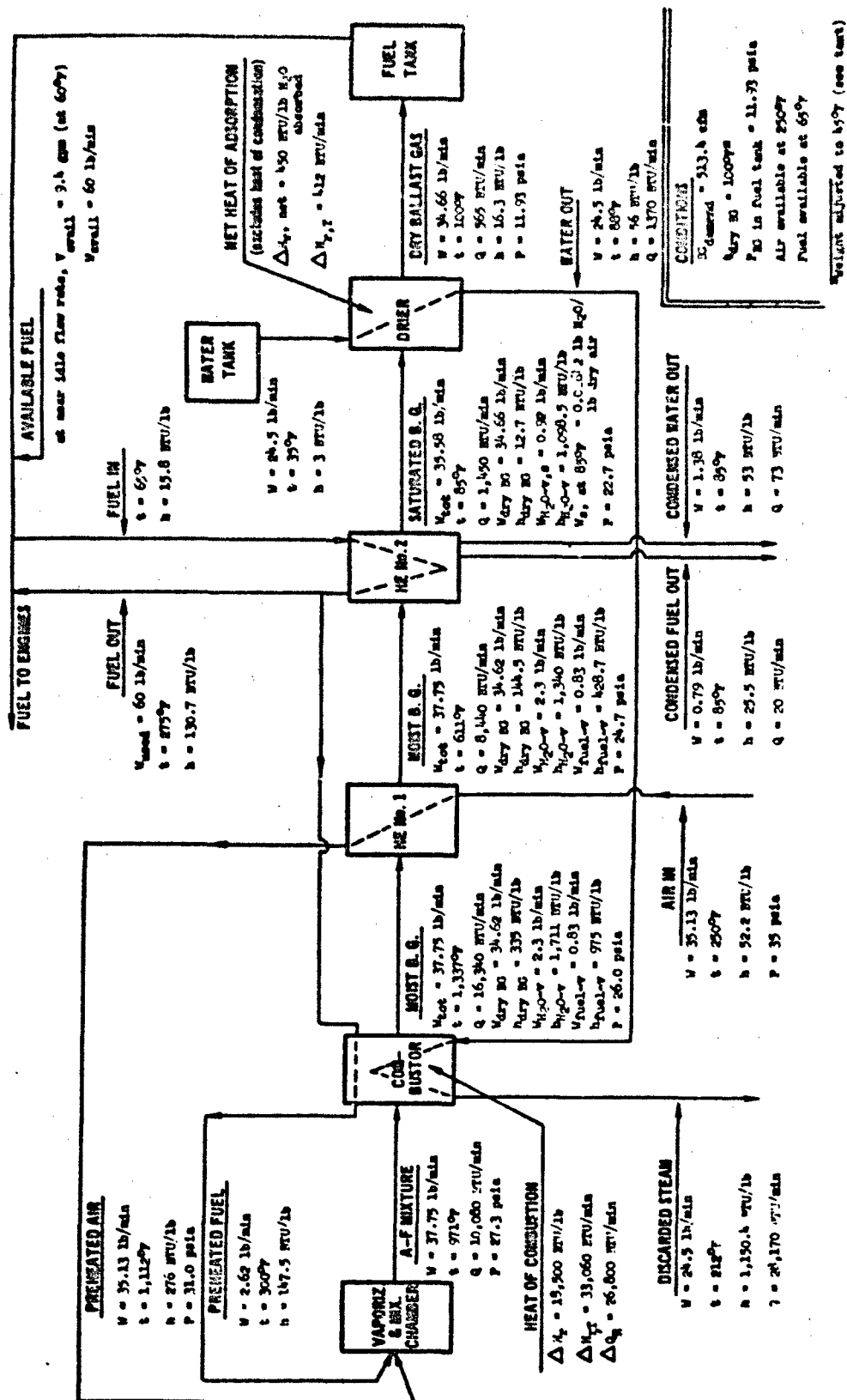


FIGURE 47. HEAT AND MASS BALANCE: DESIGN CONDITIONS FOR C-141 AIRCRAFT

Quantity of water removed in gas drier	0.92 lb/min
Quantity of fuel condensed in HE 2	0.79 lb/min
Amount of dry BG delivered to FT	34.7 lb/min
Amount of cooling water required	24.5 lb/min
Amount of fuel necessary as coclant	60 lb/min

1. Equipment Design

The foregoing permit sizing and design of the components of the inerting subsystem, which is based on peak demand for ballast gas. Details of the design and weight calculations are given in Appendix I. Results are summarized below.

(1) Weights^a

(a) Air and Fuel Feed Equipment

Supply piping	19.4 lb
Spray nozzle assembly	0.5
Vaporization chamber (Hastelloy C)	46
Heater	7
Outlet piping	1.6
Extra for fittings	0.5
Total	75 lb

(b) Combustor

Catalyst	9.9 lb
Screens (6)	27.2
Heating elements	8.3
Fuel preheating tubing	1.7
Cooling tubing	128.2
Duct and baffles (Hastelloy C)	127.7
Total	303.0 lb

^aBased on use of 316-SS except where otherwise specified.

(c) Heat Exchanger No. 1 (HE 1)

Cooling tubing	605 lb
Duct (Hastelloy C)	168
Total	<u>773 lb</u>

(d) Heat Exchanger No. 2 (HE 2)

Cooling tubing	380 lb
Duct (Hastelloy C)	103
Fuel booster pump	17
Total	<u>500 lb</u>

(e) Drier

Outer walls (aluminum)	62 lb
Cooling tubing (aluminum)	224
Desiccant	530
Filter, screens	20
Water tank and water	176
Total	<u>1,012 lb</u>

Only one desiccant, CaCl_2 , is used because it allows the BG to leave with 1,320 ppm V/V under design conditions, which satisfies the target. Since air is available under pressure at all times, it is used to push the inerting system cooling water out of the tank and through the cooling coils. Therefore, the water pump is eliminated.

(f) Total Subsystem

<u>Component</u>	<u>Pounds</u>	<u>%</u>
Drier	1,012	38
HE 1	773	29
HE 2	500	19
Combustor	303	11
Feed Streams	75	3
	<u>2,663</u>	<u>100</u>

(2) Dimensions

The C-141 inerting subsystem as conceived for this study resembles the tactical aircraft subsystem. Except for the vaporization chamber, which has the usual double-cone configuration, the various components are connected end-to-end to make up a rectangular duct whose cross-section varies somewhat according to the size of each component. Strung out in this way, overall length of the subsystem is about 13.5 feet. The dimensions of each component are as follows:

	<u>Height or Dia., ft</u>	<u>Width, ft</u>	<u>Length, ft</u>
VC	1.25 max.	---	5.33
Outlet Pipe			0.33
Combustor	1.04	2.5	1.5
HE 1	2	2.5	1.75
HE 2	1	2.5	1.83
Drier	2	2.5	2.75

(3) Discussion of Weight and Size

The toleration of a higher concentration of water vapor in the BG, as compared to the other case analyses, eases the demand for drier performance, and makes possible the use of a single desiccant. Nevertheless, the drier remains as the heaviest item, representing 38% of the total subsystem. It is believed that further study of the drier could lead to a significant weight reduction, because the unit is now overdesigned with respect to capacity. This is due to the fact that design guidelines for space velocity and efficiency dictate the size and weight of the bed to the extent that the desiccant has capacity for 230 flight-hours, (far in excess of target). Further calculations using other desiccants, smaller grain size, and possibly a booster pump for increased static pressure, could well be fruitful.

The weight of HE 1 is about in the same relative position as it is in the case of the tactical aircraft. It is not unreasonably large for a gas-to-gas exchanger, considering the amount of preheat required by the combustion air.

The weight of HE 2 is brought down to the level shown by introducing a circulating fuel loop for cooling purposes during the design period, while BG demand is high, yet fuel demand by the engines is low.

The total subsystem weight shown above represents 1.8% of the initial fuel load, which is the lowest of the values generated in this study. The prospects for substantial reduction in weight center around the drier in particular, and optimization studies in general.

SECTION VI

CONCLUSIONS

The concept for inerting aircraft fuel tanks with ballast gas generated by catalytic combustion of a small fraction of the fuel load is technically feasible. In an aircraft fueled for long-distance passenger service (the SST), only 0.006% of the initial fuel load would be used for inerting in a typical 3-hour flight. In a tactical aircraft situation, the corresponding figure is 0.011% for a representative 155-minute mission.

Any inerting subsystem that functions via control of the oxygen content of the fuel tank ballast gas must contend with the problem of widely fluctuating demand. In the tactical aircraft, for example, ballast gas demand ranges from 0.08 lb/min during level flight under cruise conditions to 11 lb/min during a powered dive, an increase of more than one-hundred-fold.

In the present subsystem, nitrogen makes up about 74% of the inert ballast gas. The effect of demand on conversion level, hence the combustor exit gas composition, varies as follows for JP-7 fuel:

	Percent by Volume	
	<u>96% Conversion</u>	<u>75% Conversion</u>
Nitrogen	72.9	73.9
Water	13.7	10.9
Carbon dioxide	11.2	8.7
Carbon monoxide	1.2	1.0
Oxygen	0.8	5.0
Fuel	0.2	0.5
	<u>100.0</u>	<u>100.0</u>

The rate of conversion of oxygen in this system is directly proportional to the concentration of fuel; hence operation with an excess of fuel is indicated. Up to 300% excess propane fuel appears to cause only a temporary increase in the production of coke. Deposition of coke equivalent to 10% carbon from a relatively poor quality of JP-4 fuel did not have any adverse effect on catalyst performance.

The catalyst tested most extensively can provide a free oxygen content well below the target level (2-9%) for periods in excess of 50 hours, without regeneration. Using propane fuel, the deactivation after 60 hours (with 100 to 300% excess fuel) is equivalent to a 10% decrease in conversion at a given temperature, or a 35°C higher temperature for the same conversion. Little or no loss in performance was observed as a result of 60 hours on stream using 100% excess of JP-4 fuel.

Results obtained in the 60-hour test with JP-4 fuel did not show the need for regeneration, and no conclusion can be drawn as to the ultimate extent of catalyst use before regeneration is necessary. Regeneration is accomplished easily using a gas containing about 4% oxygen, with provision to heat the catalyst to approximately 400°C (752°F).

For optimum results (grading off catalyst activity with thermal stability) combustion temperature should be regulated at about 725°C (1337°F). When using boiling water in finned cooling coils for cooling a radial reactor in which all coils are submerged in catalyst, the volume of the combustion zone is dictated by the required coil surface area. In a preliminary radial reactor design, the combustion zone volume as determined by heat transfer is 6 times the volume as determined by the catalyst activity. The situation is more favorable in a segmented design, using unsubmerged coils, which weighs about 45% of a radial reactor giving the same conversion.

Depending on conversion level, from 11 to 14% of water is present in the combustor exit gases. Reduction to the target level of 5 ppm requires a heat sink to absorb the heats of condensation and absorption, and to cool the gases to ~65°F. If such a heat sink is unavailable, only the use of a water reactant such as calcium carbide can satisfy the target water level requirement. Part of the heat is conveniently removed by exchange with combustion air requiring preheat, and with fuel being pumped to the engines. In situations (the SST) where the fuel coolant is at times not available below 300°F, additional cooling (to ~100°F) and some condensation can be accomplished by exchange with water being pumped to the combustor coils. If a supply of cooling water for the inerting system is assumed, the ballast gas can be dried at a temperature low enough to remove almost all of the combustion water. (At a drier temperature of 150°F, >99.99% removal is effected, and the dry ballast gas contains 10 ppm water.)

Optimization of the size and weight of the gas drier may indicate use of either one or two drying agents, (one chosen for efficiency and the other for capacity). The capacities estimated for the various cases analyzed in this study range from 50 to 230 flight-hours, without regeneration. Regeneration is accomplished by passing a gas heated to 450-550°F through the drier.

This type of inerting system gives previously unavailable control over the moisture content of the fuel tank ballast gas. Its use at low altitudes in humid climates, where dewpoints commonly reach 75°F (30,000 ppm volume) or higher, can prevent the introduction of substantial quantities of water to the fuel. The benefit in terms of reduced microbiological corrosion effects may be substantial.

Although not confirmed by actual test, it is indicated that the subsystem is capable of operating at altitudes from zero to 80,000 feet. The lower partial pressure of the reactants in the combustor feed gases at the maximum altitude would affect adversely the rate of conversion, but the reduced demand (weight basis) would tend to offset this effect. Moreover, the conversion level could be increased by enriching the combustor feed mixture while operating at high altitudes.

The weight of the inerting subsystem including equipment, catalyst, agents and cooling water supply, represents 1.8% of the initial fuel supply for the typical C-141 aircraft mission. The corresponding figure for "normal" flights in the SST is 2.3%, and an SST mission that includes an emergency powered dive would require 4.1%. The tactical aircraft carries a proportionately smaller initial fuel load, and has powered dives in typical missions; the inerting subsystem therefore represents 6.4% of the initial fuel weight.

In most instances, the heaviest component is the gas drier. It represents 35-61% of the subsystem weight, in the cases considered here. Weight savings could be realized if other means of negating the effects of water in the fuel tanks were employed, making it possible to raise the ballast gas water concentration limit.

Rivalling the gas drier in weight is the gas-to-gas exchanger where combustion products are cooled while preheating the air and fuel. This represents from 21 to 38% of the subsystem weight. Alternate means of preheating and cooling these gas streams have not been investigated.

A reduction in weight can be effected through relaxation of the performance requirements during dives, when ballast gas demand is about 100 times greater than it is during level flight at full power. Conceptual design calculations were made on the basis of 75% conversion during dives, equivalent to approximately 5% oxygen in the dry ballast gas. If conversion during dives is limited to 60%, giving 8.7% oxygen in the dry ballast gas, the subsystem weight could be reduced by 5-10%.

A substantial reduction in weight is to be expected upon optimization with respect to materials of construction to be used, and design of the principal components. Weights given herein are developed through techniques normally used for industrial process equipment, and flightweight hardware techniques remain to be applied.

SECTION VII
RECOMMENDATIONS

1. Make a critical review of the conceptual designs and subsystem performance requirements, with emphasis on selection of priority areas for weight reduction, and estimation of the potentially attainable performance-weight relationships.
2. Design, construct and install a fractional-scale breadboard inerting subsystem. Design should be generated with input from manufacturers of flightweight hardware. Include control instrumentation.
3. Employ breadboard unit and other apparatus to test and evaluate under simulated flight conditions:
 - a. Combustor
 - startup methods
 - temperature control
 - regeneration (need, frequency)
 - effects of variations in operating mixtures, flow rate, pressure
 - catalyst life
 - b. Gas Drier
 - type and size of desiccant
 - flow rate and pressure effects
 - regeneration and life of desiccant
 - fuel effects
 - c. Heat Exchangers
 - flow rate and pressure effects
 - fouling
 - tubing design and materials
 - d. Fuel Feed Methods
 - best performance-weight combination

4. Study the reduction in weight available through use of alternate design concepts such as:
 - use of a mechanical fuel atomizer
 - use of a ballast gas reservoir to reduce peak demand
 - preheating of combustion air by reacting a portion thereof with fuel, then recombining
5. Study the application of advanced materials of construction and lightweight hardware design methods to the achievement of minimum component weights. Incorporate results from the breadboard tests, and from the alternate design concept studies. Carry out scaling and optimization studies.
6. Examine the effect on fuel quality of its passage through the inerting subsystem unreacted.
7. Study logistics and servicing needs, including replacements, cleaning, and routine maintenance.

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The feasibility of inerting the ullage spaces in aircraft fuel tanks via a catalytic combustion technique is evaluated. The technique utilizes nitrogen from the surrounding atmosphere as the principal component of the ballast gas admitted to the tanks. Free oxygen is reduced to safe levels by means of catalyzed reaction with a small fraction of the aircraft fuel. Before the combustion gases are admitted to the fuel tanks, the water content is reduced by condensation and contact with a desiccant. Experiments were conducted to select and evaluate catalysts for the combustion reaction, and desiccants for water removal. Heat and material balances were prepared. Experimental and literature data were used for conceptual designs of inerting equipment that would provide target performance at all times (including powered dives) during missions typical of a tactical aircraft, a military transport, and the SST. Based on these unoptimized, preliminary designs, it was determined that complete inerting protection and control over the water admitted to the fuel tanks can be provided at a penalty of from .8% (transport) to 6.4% (tactical) of the initial fuel weight. These figures reflect industrial plant equipment weights, and substantial reductions are expected through use of lightweight equipment of optimized design. Recommendations are made for further study and development.

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